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Follow-on Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation

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EXECUTIVE SUMMARY

The Hanford Site, in southeast Washington State, is preparing to disposition approximately 56,000,000 gallons (56 Mgal) of radioactive and chemically hazardous wastes currently stored in underground tanks at the site. Tank wastes will be divided into a high-activity fraction and a low-activity fraction for subsequent treatment and disposition. A waste processing and treatment facility, the Waste Treatment and Immobilization Plant (WTP), will include the high-level waste (HLW) vitrification facility (WTP HLW Vitrification Facility) for immobilizing the high-activity fraction and a low-activity waste (LAW) vitrification facility (WTP LAW Vitrification Facility) for immobilizing the low-activity fraction. Both facilities will use vitrification technology to immobilize the Hanford tank wastes in a glass waste form.

The volume of LAW to be treated and disposed of following waste retrieval and WTP operations will exceed the planned processing capacity of the WTP LAW Vitrification Facility. ORP-11242, *River Protection Project System Plan*,[1] estimates a shortfall in LAW treatment capacity of approximately 56 Mgal, approximately 50% of the projected LAW volume.[2] To maintain the planned tank waste processing mission schedule, the U.S. Department of Energy (DOE) will require additional LAW treatment capacity (termed "supplemental LAW") external to the WTP process. LAW must be solidified by a treatment technology before the waste can be permanently disposed of in an approved DOE on-site disposal facility or a commercial (state or U.S. Nuclear Regulatory Commission [NRC]-licensed) off-site mixed low-level waste disposal facility. A decision on the approach to supplemental LAW treatment, processing, and disposal has not yet been made.

Section 3125 of the Fiscal Year 2021 National Defense Authorization Act (NDAA21),[3] directs DOE to enter into an arrangement with a Federally Funded Research and Development Center (FFRDC) to conduct an analysis that:

> *"...shall be designed, to the greatest extent possible, to provide decisionmakers with the ability to make a direct comparison between approaches for the supplemental treatment of low-activity waste at the Hanford Nuclear Reservation based on criteria that are relevant to decision making and most clearly differentiate between approaches."*

In accordance with Section 3125, this analysis provides an assessment of the following:

- The most effective potential technology for supplemental treatment of LAW that will produce an effective waste form
- The differences among approaches for the supplemental treatment of LAW considered as of the date of the analysis
- The compliance of such approaches with the technical standards described in Section 3134 of the NDAA for Fiscal Year 2017 (NDAA17)[4]
- The differences among potential disposal sites for the waste form produced through such treatment, including mitigation of radionuclides, including technetium-99 (^{99}Tc), selenium-79 (^{79}Se), and iodine-129 (^{129}I), on a system level

[1] ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

[2] The volume of waste to be treated is much greater than the volume currently in the waste tanks because water is added during retrieval, staging, and pretreatment processes.

[3] *National Defense Authorization Act for Fiscal Year 2021*, Public Law 116–283, January 1, 2021.

[4] *National Defense Authorization Act for Fiscal Year 2017*, Public Law 114–328, December 23, 2016.

- Potential modifications to the design of facilities to enhance performance with respect to disposal of the waste form to account for: (1) regulatory compliance, (2) public acceptance, (3) cost, (4) safety, (5) expected radiation dose to maximally exposed individuals over time, and (6) differences among disposal environments
- Approximately how much and what type of pretreatment is needed to meet regulatory requirements regarding long-lived radionuclides and hazardous chemicals to reduce disposal costs for radionuclides
- Whether the radionuclides can be left in the waste form or economically removed and bounded at a system level by the performance assessment of a potential disposal site and, if the radionuclides cannot be left in the waste form, how to account for the secondary waste stream
- Other relevant factors relating to the technology, including: (1) costs and risks in delays with respect to tank performance over time, (2) consideration of experience with treatment methods at other sites and commercial facilities, and (3) outcomes of the DOE Office of Environmental Management Test Bed Initiative at Hanford.

In addition to consideration of vitrification and fluidized bed steam reforming technologies, Section 3125 of NDAA21 requires the FFRDC team to perform additional analysis of grout treatment options building on the analysis in the FFRDC report for Section 3134 of NDAA17. Because this is a follow-on analysis, some of the summary and overview information presented is repeated from the NDAA17 analysis.

The focus of the FFRDC analysis is on technologies and approaches, and the FFRDC team is made up of technical experts in appropriate disciplines from the national laboratories, academia, industry, and private institutions. The NDAA21 also requires a concurrent review of the analysis by a committee of technical experts selected by the National Academies of Science, Engineering, and Medicine.

The FFRDC team concluded that vitrification and grouting technologies are technically viable for supplemental treatment of LAW. These approaches do not pose high technical risks and there is high confidence that any unforeseen technical issues can be resolved. In contrast, fluidized bed steam reforming (FBSR) implementation at Hanford, while viable, would be a first-of-a-kind technology implementation, with the potential for substantial technical challenges.

The FFRDC team found significant differences among alternatives in cost, duration, and likelihood of successful project completion. The annual and total cost to implement capital projects for some of the proposed alternatives is significantly greater than for others. Additionally, based on benchmark budget scenarios, non-grout technologies pose a significant risk of extended processing durations that would increase the risk of further deterioration of the waste storage tanks prior to waste retrieval/processing. Only alternatives employing grout technology appear to be technically viable, low-to-moderate risk, and flexible enough to implement under a range of constrained budget scenarios without significant impact to the WTP HLW Vitrification Facility mission completion schedule. Alternatives with off-site immobilization and disposal offer additional advantages due to their ability to begin processing much sooner. This finding is robust under the full range of sensitivity analyses performed by the FFRDC team.

The FFRDC team makes the following recommendation:

DOE should expeditiously secure and implement multiple pathways for off-site grout solidification/ immobilization and disposal of LAW in parallel with the direct-feed low-activity waste (DFLAW) vitrification process.

This recommendation is based on a comprehensive evaluation of multiple alternatives considering (1) long-term effectiveness (environmental and safety risk after disposal), (2) implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration), (3) likelihood of successful mission completion (including technical, engineering, and resource-related risks), and (4) lifecycle costs (discounted present value). The intent of multiple pathways is to provide parallel contractual agreements with multiple facilities for off-site solidification/immobilization and disposal to minimize risks associated with potential facility- or state-specific implementation challenges.

The recommended approach can be beneficial in many ways, as the approach:

- Provides the capability to achieve the most rapid reduction in the amount of waste stored in the Hanford single-shell tanks and double-shell tanks by using available off-site solidification/ immobilization and disposal capacity, and therefore results in the most rapid reduction in risk to human health and the environment attributed to potential future unplanned tank waste releases.
- Provides additional long-term environmental protection, including to the aquifers underlying the Hanford Site and the Columbia River, by disposing of a significant portion of the inventory of risk-driving constituents (e.g., ^{99}Tc, ^{129}I) at off-site facilities that are located in geologic settings with low infiltration and do not have credible pathways to potable water aquifers.
- Provides flexibility in the available treatment technologies and disposal pathways, and reduces the potential for individual choke points to further delay the Hanford tank waste treatment and disposal mission. Concurrent LAW vitrification and solidification/immobilization treatment and disposal pathways would allow LAW routing based on waste characteristics to the most appropriate and efficient treatment technology.
- Provides opportunity to reduce or eliminate the need for future additional treatment capability and affords time to gain experience with the DFLAW vitrification process and grout solidification/ immobilization treatment prior to making such decisions.
- Minimizes financial demands and reduces mission duration and lifecycle costs.

Specific details for implementation of this recommendation will need to be identified through DOE processes, multi-party negotiations, and the National Environmental Policy Act (NEPA)[5] process. Regulatory and stakeholder participation procedures and government-to-government interactions with Tribal Nations[6] will need to be implemented using established formal processes.

This report describes the FFRDC team's analysis and results, which are intended to inform the decision-makers who will ultimately select approaches and technologies for supplemental LAW treatment and disposition.

[5] *National Environmental Policy Act of 1969*, 42 USC 4321, et seq.

[6] Tribal Nation treaty rights at the Hanford Site are addressed by DOE and the Tribes through government-to-government consultations pursuant to DOE O 144.1, *Department of Energy American Indian Tribal Government Interactions and Policy*.

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^{3}H	hydrogen-3
^{14}C	carbon-14
^{79}Se	selenium-79
^{85}Kr	krypton-85
^{90}Sr	strontium-90
^{99}Tc	technetium-99
^{127}I	iodine-127
^{129}I	iodine-129
AAR	Association of American Railroads
ACI	American Concrete Institute
AEA	Atomic Energy Act
ALARA	as low as reasonably achievable
AoA	analysis of alternatives
ARP	actinide removal process
ASTM	ASTM International
BBI	Best Basis Inventory
BDAT	Best Demonstrated Available Technology
BFS	blast furnace slag
BSR	bench-scale reformer
BWF	Bulk Waste Disposal and Treatment Facilities
CAA	Clean Air Act
CAPEX	capital expenditure
CAW	Class A West
CBO	Congressional Budget Office
CD	Critical Decision
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CETL	Clemson Engineering Technologies Laboratory
CFR	Code of Federal Regulations
CIF	Consolidated Incineration Facility
CLSM	controlled low-strength material
CNWRA	Center for Nuclear Waste Regulatory Analysis
CO	carbon monoxide
CO	Colorado
CoC	contaminant of concern
CoPC	constituent of potential concern
Cr	chromium
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
CRR	carbon reduction reformer
Cs	cesium
CSSX	caustic-side solvent extraction

CST	crystalline silicotitanate
CSTR	continuous stirred tank reactor
CWA	Clean Water Act
D&D	decontamination and decommissioning
DBVS	Demonstration Bulk Vitrification System
DF	decontamination factor
DFHLW	direct-feed high-level waste
DFLAW	direct-feed low-activity waste
DMR	denitration and mineralizing reformer
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-EM	U.S. Department of Energy, Office of Environmental Management
DOE-OPT	U.S. Department of Energy, Office of Packaging and Transportation
DOT	U.S. Department of Transportation
DRC	Division of Radiation Control
DRF	dry reagent formulation
DSS	double-shell slurry
DSSF	double-shell slurry feed
DST	double-shell tank
DU	depleted uranium
DWPF	Defense Waste Processing Facility
DWS	Drinking Water Standards
DWTS	dry waste transfer system
Ecology	Washington State Department of Ecology
EDTA	ethylenediamine-tetraacetic acid
EIS	environmental impact statement
EM	U.S. Department of Energy, Office of Environmental Management
EMCBC	U.S. Department of Energy, Environmental Management Consolidated Business Center
EMF	Effluent Management Facility
EPA	U.S. Environmental Protection Agency
ERDF	Environmental Restoration Disposal Facility
ETF	Effluent Treatment Facility
EWIS	Electronic Waste Information System
FA	fly ash
FBSR	fluidized bed steam reforming
FFRDC	Federally Funded Research and Development Center
FMF	Fuel Manufacturing Facility
FWF	Federal Waste Disposal Facility
FY	fiscal year
GAAT	Gunite and Associated Tanks
GAC	granular activated carbon
GAO	U.S. Government Accountability Office

GCL	geosynthetic clay liner
GDU	grout disposal unit
GFC	glass-forming chemical
GTCC	Greater-than-Class C
GWPL	groundwater protection level
GWQS	Ground Water Quality Standard
HEDTA	hydroxyethylethylenediaminetriacetic acid
HELP	Hydrologic Evaluation of Landfill Performance
HEPA	high-efficiency particulate air
HFPEM	High-Level Waste Feed Preparation and Effluent Management
HIC	high integrity container
HLVIT	high-level [mixed radioactive waste] vitrification
HLW	high-level waste
HRWR	high-range water reducer
HVAC	heating, ventilation, and air conditioning
HWMA	Hazardous Waste Management Act
I	iodine
IAEA	International Atomic Energy Agency
IC	institutional control
ICV	In-Container Vitrification[1]
IDF	Integrated Disposal Facility
ILAW	immobilized low-activity waste
ILW	intermediate level waste
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
IOC	iron oxide catalyst
IP	industrial package
IQRPE	Independent Qualified Registered Professional Engineer
ISO	International Organization for Standardization
IWTU	Integrated Waste Treatment Unit
IX	ion exchange
K_d	dissociation constant
K_{sp}	solubility product constant
LANL	Los Alamos National Laboratory
LARW	low-activity radioactive waste
LAW	low-activity waste
LAWPS	Low-Activity Waste Pretreatment System
LAWST	low-activity waste supplemental treatment
LCC	lightweight cellular concrete
LCRS	leachate collection and removal system
LDR	Land Disposal Restrictions

[1] In-Container Vitrification (ICV) is a trademark of Veolia, Boston, Massachusetts.

LDS	leak detection system
LERF	Liquid Effluent Retention Facility
LFE	low-activity waste feed evaporator
LLHH	long, large, and/or heavy hazardous
LLRW	low-level radioactive waste
LLW	low-level waste
LSA	low specific activity
LSW	liquid secondary waste
MCC	modular concrete canister
MCL	maximum contaminant level
MCU	modular caustic-side solvent extraction unit
MDL	method detection limit
MF	MasterFlow®
MIMS	Manifest Information Management System
MLLW	mixed low-level waste
MOE	measure of effectiveness
MST	monosodium titanate
MT	metric ton
NaOH	sodium hydroxide
NARM	naturally occurring and accelerator-produced radioactive material
NAS	National Academy of Sciences
NASEM	National Academy of Sciences, Engineering, and Medicine
NCP	National Contingency Plan
NDA	Nuclear Decommissioning Authority
NDAA	National Defense Authorization Act
NDAA17	Fiscal Year 2017 National Defense Authorization Act
NDAA21	Fiscal Year 2021 National Defense Authorization Act
NEPA	National Environmental Policy Act
NNSS	Nevada National Security Site
NORM	naturally occurring radioactive material
NO_x	nitrogen oxides
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NRSB	Nuclear and Radiation Studies Board
NSDWR	National Secondary Drinking Water Regulations
NY	New York
O	Order
OAG	Ogallala, Antlers, and Gatuna
OH	Ohio
OMB	U.S. Office of Management and Budget
OPC	ordinary portland cement
OPEX	operations expenditure

ORNL	Oak Ridge National Laboratory
ORP	U.S. Department of Energy, Office of River Protection
OU	Operable Unit
PA	performance assessment
PCB	polychlorinated biphenyl
PCT	product consistency test
PE	performance evaluation
Perma-Fix Northwest	Perma-Fix Northwest, Inc.
PGF	process gas filter
PNNL	Pacific Northwest National Laboratory
PT	Pretreatment Facility
PUF	pressurized unsaturated flow
PUREX	plutonium-uranium extraction
PV	present value
R&D	research and development
RADTRAN	Radioactive Material Transport
RCRA	Resource Conservation and Recovery Act
RCW	Revised Code of Washington
RD&D	research, development, and demonstration
REDOX	reduction-oxidation
RLWTF	Radioactive Liquid Waste Treatment Facility
RML	radioactive material license
ROD	record of decision
RPP	River Protection Project
SALDS	state-approved land disposal site
SAS	steam atomized scrubber
SBS	submerged bed scrubber
SBWW	sodium-bearing wastewater
SCDHEC	South Carolina Department of Health and Environmental Control
SCR	selective catalytic reduction
SDU	Saltstone Disposal Unit
SDWA	Safe Drinking Water Act
Se	selenium
SER	Safety Evaluation Report
SLAW	supplemental low-activity waste
SLDS	secondary leak detection system
SMCL	secondary maximum contaminant level
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SPF	Saltstone Production Facility
SPFT	single-pass flow-through

SPRU	Separations Process Research Unit
sRF	spherical resorcinol-formaldehyde
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SSR	Specific Safety Requirements
SST	single-shell tank
SSW	solid secondary waste
START	Stakeholder Tool for Assessing Radioactive Transportation
SVOA	semivolatile organic analyte
SVOC	semivolatile organic compound
SWPF	Salt Waste Processing Facility
TAC	Texas Administrative Code
TBI	Test Bed Initiative
Tc	technetium
TC&WM	Tank Closure and Waste Management
TCAS	Texas Constitution and Statutes
TCEQ	Texas Commission on Environmental Quality
TCLP	Toxicity Characteristic Leaching Procedure
TCO	thermal catalytic oxidizer
TDS	total dissolved solids
TEDF	Treated Effluent Disposal Facility
TFF	Tank Farm Facility
TFPT	Tank Farms Pretreatment
THOREX	thorium extraction
TI	transportation index
TO	thermal oxidizer
TOC	total organic carbon
TOE	total operating efficiency
TPA	Tri-Party Agreement
TRAGIS	Transportation Routing Analysis Geographic Information System
TRL	technology readiness level
TRU	transuranic
TSCR	tank-side cesium removal
TSD	treatment, storage, and disposal
TSDF	Texas Storage and Processing Facility
TVS	Transportable Vitrification System
TWINS	Tank Waste Information Network System
TX	Texas
U.K.	United Kingdom
U.S.	United States
UAC	Utah Administrative Code
UDEQ	Utah Department of Environmental Quality

UMTRA	Uranium Mill Tailings Remediation Action
UT	Utah
UTS	Universal Treatment Standards
UV/OX	ultraviolet/oxidation
UWQB	Utah Water Quality Board
VHT	vapor hydration test
VLAW	vitrified low-activity waste
VOA	volatile organic analyte
VOC	volatile organic compound
VSL	Vitreous State Laboratory of The Catholic University of America
VTD	vacuum thermal desorption
WA	Washington
WAC	Washington Administrative Code
WCS	Waste Control Specialists, LLC
WDOH	Washington Department of Health
WebTRAGIS	Web-Based Transportation Routing Analysis Geographic Information System
WESP	wet electrostatic precipitator
WIPP	Waste Isolation Pilot Plant
WIR	Waste Incidental to Reprocessing
WRF	waste receiving facility
WRPS	Washington River Protection Solutions, LLC
WTP	Waste Treatment and Immobilization Plant
WVDP	West Valley Demonstration Project
XAS	X-ray absorption spectroscopy

1.0 INTRODUCTION

Section 3125 of the Fiscal Year 2021 National Defense Authorization Act (NDAA21), directs the U.S. Department of Energy (DOE) to enter into an arrangement with a Federally Funded Research and Development Center (FFRDC) to conduct an analysis that:

> "*…shall be designed, to the greatest extent possible, to provide decisionmakers with the ability to make a direct comparison between approaches for the supplemental treatment of low-activity waste at the Hanford Nuclear Reservation based on criteria that are relevant to decision making and most clearly differentiate between approaches.*"

In accordance with Section 3125, this analysis provides an assessment of the following:

- The most effective potential technology for supplemental treatment of low-activity waste (LAW) that will produce an effective waste form
- The differences among approaches for the supplemental treatment of LAW considered as of the date of the analysis
- The compliance of such approaches with the technical standards described in Section 3134 of the NDAA for Fiscal Year 2017 (NDAA17)
- The differences among potential disposal sites for the waste form produced through such treatment, including mitigation of radionuclides, including technetium-99 (^{99}Tc), selenium-79 (^{79}Se), and iodine-129 (^{129}I), on a system level
- Potential modifications to the design of facilities to enhance performance with respect to disposal of the waste form to account for: (1) regulatory compliance, (2) public acceptance, (3) cost, (4) safety, (5) expected radiation dose to maximally exposed individuals over time, and (6) differences among disposal environments
- Approximately how much and what type of pretreatment is needed to meet regulatory requirements regarding long-lived radionuclides and hazardous chemicals to reduce disposal costs for radionuclides
- Whether the radionuclides can be left in the waste form or economically removed and bounded at a system level by the performance assessment of a potential disposal site and, if the radionuclides cannot be left in the waste form, how to account for the secondary waste stream
- Other relevant factors relating to the technology, including: (1) costs and risks in delays with respect to tank performance over time, (2) consideration of experience with treatment methods at other sites and commercial facilities, and (3) outcomes of the DOE Office of Environmental Management Test Bed Initiative at Hanford.

In addition, Section 3125 of NDAA21 requires the FFRDC team to perform additional analysis of grout treatment options building on the analysis in the FFRDC report for Section 3134 of NDAA17. Because this is a follow-on analysis, some of the summary and overview information presented is repeated from the NDAA17 analysis.

Congress, in NDAA17 Section 3134, defines supplemental LAW as "the portion of low-activity waste at the Hanford Nuclear Reservation, Richland, Washington, that, as of such date of enactment, [December 23, 2016] is intended for supplemental treatment."[1] DOE's ORP-11242, *River Protection Project System Plan* (System Plan, Rev. 7), in effect on the date of enactment, identified the portion of LAW intended for supplemental treatment as: LAW that the Waste Treatment and Immobilization Plant (WTP) LAW Vitrification Facility is predicted to lack the capacity to treat without impacting the duration of the WTP high-level waste (HLW) Vitrification Facility mission. Consistent with this definition, the FFRDC follow-on report addresses alternatives to augment LAW treatment capacity for the quantity of the low-activity fraction of Hanford tank waste (LAW) that has been estimated for which the treatment capacity in the WTP LAW Vitrification Facility will be insufficient. However, the most recent System Plan (ORP-11242, Rev. 9) information was used in this analysis to include the most up-to-date information.

The focus of the FFRDC analysis is on technologies and approaches, and the FFRDC team is made up of technical experts in appropriate disciplines from the national laboratories, academia, industry, and private institutions. The NDAA21 also requires a concurrent review of the analysis by a committee of technical experts selected by the National Academy of Sciences, Engineering, and Medicine (NASEM).

This report describes the FFRDC team's analysis and results, which are intended to inform the decision-makers who will ultimately select approaches and technologies for supplemental LAW treatment and disposition.

1.1 Supplemental Treatment for Low-Activity Waste

The Hanford Site, in southeast Washington State, currently stores approximately 56,000,000 gallons (56 Mgal [210 million L]) of radioactive and chemically hazardous wastes in underground storage tanks located in 17 tank farms. Tank wastes will be divided into a high-activity fraction for treatment and disposal in a geologic repository designated for spent nuclear fuel and HLW, and a low-activity fraction of tank waste for subsequent treatment and disposition in a mixed low-level waste (MLLW) disposal facility. A waste processing and treatment facility, the WTP, will include the HLW Vitrification Facility for immobilizing the high-activity fraction and the WTP LAW Vitrification Facility for immobilizing the low-activity fraction. Both facilities will use vitrification technology to immobilize the Hanford tank wastes in a glass waste form.

The System Plan (ORP-11242) estimates that the expected WTP LAW vitrification treatment capacity will not be able to treat all the LAW expected to be generated during the tank waste mission, with a shortfall in LAW treatment capacity of approximately one half of the LAW volume (56 Mgal [210 million L][2]). To maintain the tank waste processing mission schedule duration specified in the baseline case of ORP-11242 (Rev. 9), DOE will require additional LAW treatment capacity (termed "supplemental LAW") external to the WTP process. The LAW must be solidified by a treatment technology before the waste can be permanently disposed of in an approved DOE on-site disposal facility or a commercial (state or U.S. Nuclear Regulatory Commission [NRC]-licensed) off-site MLLW disposal facility.

LAW is characterized as a "mixed waste" containing both radioactive and hazardous chemical constituents. Compared to the high-activity fraction of tank waste, the overall radioactivity content of the LAW is significantly lower. Pretreatment includes filtration for solids removal and removal of cesium by ion exchange (IX) using an elutable resin or absorption onto crystalline silicotitanate (CST). The LAW treatment process concludes with immobilization of the waste into a solid form (e.g., glass, grout) prior to disposal. The requirements for the immobilized form will vary depending on the disposal site.

[1] NDAA21 Section 3125, which governs the FFRDC follow-on report, refers to NDAA17 Section 3134.

[2] The volume of waste to be treated is much greater than the volume currently in the waste tanks because water is added during retrieval, staging, and pretreatment processes.

Some of the metals and organic chemicals expected to be in LAW are regulated under the *Resource Conservation and Recovery Act of 1976* (RCRA), which sets Land Disposal Restriction (LDR) standards that must be met through treatment or other regulatorily approved approaches. Other constituents, such as nitrates, are regulated through *Safe Drinking Water Act of 1974* (SDWA) limits, which establish maximum contaminant levels for these constituents.

LAW treatment and disposal must meet requirements established for protection of human health and the environment, including specifically for (1) metals and organic chemicals (established under RCRA), (2) radionuclides (established under the *Atomic Energy Act of 1954* [AEA]), and (3) additional chemicals (e.g., nitrates) (as established under state and other federal regulations).

1.2 Waste Treatment Technologies Analyzed

The three primary LAW treatment technologies identified in the NDAA21 (and NDAA17) for analysis are vitrification, fluidized bed steam reforming (FBSR), and grouting. However, each of these primary immobilization technologies has different processing steps to achieve implementation, including pretreatment steps, offgas and effluent treatment prior to discharge to the environment, and treatment and disposal of liquid and solid wastes that contain constituents requiring immobilization prior to disposal in a licensed/permitted land disposal facility.

Vitrification – This high-temperature technology blends the liquid LAW with glass-forming materials at approximately 1,150°C, forming a mixture that incorporates the radionuclides and metals into a "primary" monolithic glass waste form, but significant fractions of semi-volatile species are emitted from the melter requiring an extensive offgas treatment system to capture these species and mitigate release to the stack. The vitrification and offgas systems destroy most LDR organic compounds and some of the nitrates. Because the water in the LAW is not incorporated into the glass, practically all the water initially present in LAW and produced in the process, primarily from operations of the offgas system, is managed as liquid "secondary" waste, which contains radionuclides, metals, and organic chemicals not captured or destroyed by the glass-forming process step.

The solid secondary wastes (e.g., offgas filters, activated carbon, used equipment) from the vitrification process would be embedded in cementitious material (similar to the "Grouting" description below) prior to disposal, while some of the liquid secondary wastes will be immobilized using grouting for subsequent disposal and some will be treated with other wastewater streams, with the treated wastewater released in accordance with approved discharge permits. DOE has successfully operated tank waste vitrification facilities for the high-activity fraction of tank waste at the Savannah River Site (SRS) and the West Valley Demonstration Project (WVDP), but the HLW streams were significantly different from Hanford LAW and throughput requirements were much lower.

Fluidized bed steam reforming – This high temperature technology blends the liquid LAW with dry fuel materials and inorganic materials at approximately 750°C, to react, form, and incorporate most of the radionuclides and metals into dry granular mineral particles. The granular particles can be further encapsulated in a cement-like geopolymer. A dry, catalytic offgas treatment system is used, so no liquid offgas system secondary wastes are produced. Solid secondary wastes (spent carbon sorbent and air filters) are similar to those from vitrification but are anticipated to have less radioactivity because of improved capture and lower operating temperatures. FBSR is expected to destroy essentially all LDR organic compounds and nitrates, converting them to carbon dioxide, nitrogen, water, and residual nitrogen oxides (NO_x). DOE has constructed an FBSR facility for treating wastes with different characteristics from Hanford LAW at the Idaho National Laboratory (INL), which is expected to begin operations to treat approximately 900,000 gallons (3.4 million L) of tank waste in 2023.

Grouting – This technology operates at room temperatures and blends the LAW with dry inorganic materials (e.g., portland cement and blast furnace slag) to produce a monolithic cement-like waste form. Pretreatment may be required to destroy or separate LDR organic chemicals if concentrations are measured/determined to be above the regulatory limits. Radionuclides, metals, and nitrates are incorporated into the grout. Secondary wastes from this process are minimal because the water in the LAW is chemically incorporated into the waste form. Grouting systems that have operated throughout the DOE complex include two low-activity tank waste facilities at SRS and WVDP. Grouting is a common practice for treating commercial low-level radioactive waste and is a U.S. Environmental Protection Agency (EPA)-recommended and common practice for wastes containing metals and other inorganic components.

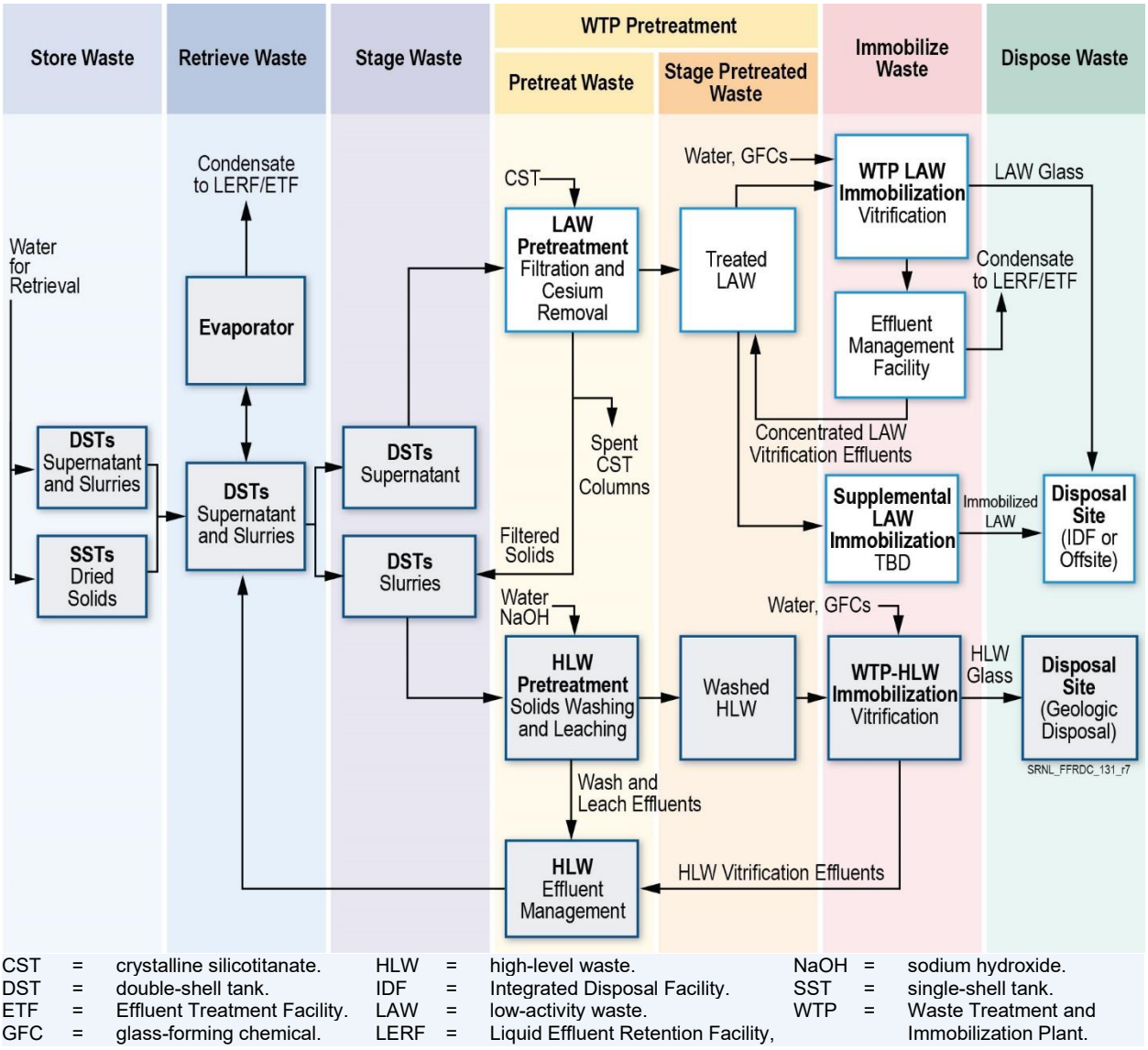
1.3 Process Overview

1.3.1 Overall Hanford Waste Treatment Process Overview

Supplemental treatment of LAW is a portion of a larger program to retrieve, qualify and stage, pretreat, immobilize, and dispose of wastes from plutonium production at the Hanford Site. Some of the waste is currently stored as "dried" solids, called sludge or saltcake depending on the salt content, in the single-shell tanks (SST) (some supernatant liquid remains in SSTs but bulk free liquid has been removed), with the remaining portion stored as slurry or supernatant liquid in DSTs. A simplified flowsheet is shown in Figure 1.3-1 (on the next page), assuming a direct-feed HLW (DFHLW) treatment configuration. The WTP Pretreatment (PT) Facility performs the "pretreat waste" and "stage pretreated waste" functions and the effluent management for the LAW and HLW processes, but a direct-feed approach was used in the scenarios in this evaluation.

The first step in the waste treatment process is retrieval of the saltcake and sludge from the SSTs into a double-shell tank (DST), typically done by sluicing with supernatant liquids or water. Large volumes of water could be added during this process and solid salts are dissolved. Solids that remain after the water addition contain most of the long-lived radionuclides, so a solid-liquid separation is performed with resulting liquid waste staged for additional pretreatment to remove cesium while the solids are staged for additional pretreatment to further reduce the amount of salts in the slurry remaining after decanting the supernatant liquid waste (the remaining slurry is often referred to as sludge). The supernatant fraction is typically described as treated LAW once the cesium is removed, while the slurry remaining after decanting the supernatant liquid is the high-activity fraction.

Pretreatment of the high-activity fraction consists of sludge "washing", which removes additional salts from the sludge through successive addition of water and solids/liquid separation to remove additional supernatant liquid. In addition, dissolution of aluminum species from the solids using caustic leaching processes may be performed. Both the washing and leaching operations will generate additional supernatant liquid as part of the LAW that will be sent to the LAW pretreatment processes for cesium removal. The high-activity fraction (washed and/or leached slurry) will be vitrified in the WTP HLW Vitrification Facility, with the immobilized waste stored onsite until transport to a geologic disposal site. Vitrification processes do not immobilize the water from the slurries; the water is evaporated from the melter and then condensed from the melter offgas and collected along with water added during offgas treatment processes. The effluents from the WTP HLW Vitrification Facility and the WTP LAW Vitrification Facility processes will be recycled for immobilization into the glass or can be dispositioned in other ways if necessary.



CST = crystalline silicotitanate.
DST = double-shell tank.
ETF = Effluent Treatment Facility.
GFC = glass-forming chemical.
HLW = high-level waste.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
LERF = Liquid Effluent Retention Facility,
NaOH = sodium hydroxide.
SST = single-shell tank.
WTP = Waste Treatment and Immobilization Plant.

Figure 1.3-1. Simplified Diagram of Planned Tank Waste Treatment (Showing Direct-Feed High-Level Waste Process)

An evaporation process is assumed to concentrate the dilute WTP HLW Vitrification Facility effluents prior to sending these streams to LAW pretreatment, although some WTP HLW Vitrification Facility treatment streams may require processing as relatively dilute streams to prevent precipitation.

LAW pretreatment consists of filtration to remove any residual solids from the supernatant liquid, followed by cesium removal. This evaluation assumes that cesium removal is performed using CST sorbent using systems similar to the currently operating tank-side cesium removal (TSCR) unit, but the WTP PT Facility would use a different resin and would not remove the strontium. The treated LAW will be sent to the existing WTP LAW Vitrification Facility and the supplemental LAW treatment facility.

Current models assume that the WTP LAW Vitrification Facility is fed preferentially, with only remaining excess LAW sent to supplemental treatment, although this study also considers availability of parallel treatment process pathways by WTP LAW vitrification and supplemental LAW treatment where LAW can be routed to either process based on waste characteristics to achieve improved processing efficiency. The immobilized LAW will be disposed of in the existing Integrated Disposal Facility (IDF) at the Hanford Site or existing MLLW off-site disposal facilities. Liquid effluents from the WTP LAW Vitrification Facility are transferred to the Effluent Management Facility (EMF) where the effluents are evaporated from the primary offgas system. The concentrate is recycled to the WTP LAW Vitrification Facility for subsequent immobilization, while the condensate is sent to the Hanford Liquid Effluent Retention Facility/Effluent Treatment Facility (LERF/ETF) for subsequent processing and disposition.[3]

The overall tank waste treatment program continues to evolve over time, and these changes impact the volume, composition, and schedule of LAW feed that would be sent to the supplemental LAW treatment facility. Factors that influence the overall LAW mission include the timing and extent of HLW pretreatment processes, start date and achieved WTP LAW throughput during direct-feed low-activity waste (DFLAW) processing, and the efficiency of existing facilities (e.g., tank farms, 242-A Evaporator, LERF/ETF) to manage SST retrievals, waste staging and characterization, and effluent treatment. This document used schedules available in early 2022. Any changes in the WTP LAW Vitrification Facility or other tank waste treatment schedules that are not incorporated into the System Plan (ORP-11242, Rev. 9) models are not addressed.

The purpose of this document is to provide comparisons of LAW supplemental treatment technologies and capabilities, some of which are not necessarily impacted by WTP LAW vitrification processing. Demonstrating and implementing early treatment and disposal options discussed herein would help to mitigate the risk of continued tank waste storage.

1.3.1.1 Composition and Volume of Low-Activity Waste Feed to Supplemental Treatment of Low-Activity Waste

The composition and volume of feed sent to the supplemental treatment facility for LAW is highly dependent on the assumptions made for the overall flowsheet. As stated above, the sequence of tank retrievals, the amount of washing and leaching of high-activity fraction slurries, and the timing of the start of WTP HLW Vitrification Facility processing, all impact the volume of LAW to be treated. In addition, the timing of implementing the supplemental LAW treatment capability impacts the monthly volume and composition of the feed designated for supplemental treatment. Thus, any description of the feed to the facility is subject to uncertainty.

System Plan, Scenario 1B (ORP-11242, Rev. 9) was used to specify the feed vector (feed volume and composition over time) for this evaluation, and this feed vector was used to perform the initial evaluation of all alternatives. The feed vector information provided by WRPS includes monthly average volumes and compositions for the expected feed to the supplemental LAW treatment facility.

Using a fixed benchmark budget scenario, vitrification was projected to begin operations much later than the dates assumed for supplemental LAW in the System Plan, while several grout alternatives offer opportunities for an early start. To better understand the impacts of the supplemental LAW schedule on the overall and supplemental LAW missions, TOPSim model runs were performed by Washington River Protection Solutions, LLC (WRPS) in support of the supplemental LAW evaluation.

[3] The LERF/ETF provides treatment (e.g., ultraviolet/oxidation [UV/OX], filtration, ion exchange, organics separation, evaporation) of liquid effluents from existing processes, such as the 242-A Evaporator condensate, and will treat effluents from the WTP and IDF. The treated water under DFLAW will be disposed of in the State Approved Land Disposal Site (SALDS) at Hanford, while extracted contaminants are either captured in the ETF secondary treatment train that is concentrated via evaporation (brine concentrate) or is managed separately (steam stripper effluent). Brine concentrate and steam stripper effluent is then grouted for disposal at IDF. Effluents sent to LERF/ETF must meet the facility waste acceptance criteria.

These runs were used to evaluate the efficacy and impact of an early start and the impact of a fixed benchmark budget. Alternatives for FBSR were not remodeled, as the timing of the supplemental LAW implementation for FBSR was expected to more closely match the System Plan model than the other alternatives. The updated model runs were used to support capital and operating costs, but were not used for shipping or waste disposal evaluations. All shipping and waste disposal evaluations used the System Plan (Rev. 9) feed vector.

The System Plan, Scenario 1B, assumed that the WTP PT Facility was in service, whereas an assumption during this assessment was that TSCR units (or similar) would be used for LAW pretreatment. Two significant differences in the feed vector would result from the change in pretreatment system technology. First, the PT Facility design included evaporators that concentrated the feed after cesium removal. This evaporation step *is included* in the *LAW supplemental* facility functionality *in all alternatives* to minimize the impact on the waste volume to be treated. Second, the cesium removal process via absorption on CST media will also remove most of the strontium and significant portions of other species, such as plutonium. Adjustments in this analysis were made to the strontium content of the feed, but no other adjustments were made to account for removal of other species.

Table 1.3-1 and Table 1.3-2 show the feed compositions for major chemical and radiological components, and Figure 1.3-2 (on the next page) shows the expected variations in volume for the System Plan (Rev. 9), Scenario 1B feed vector.

Table 1.3-1. Chemical Species in Pretreated Low-Activity Waste (Scenario 1B)

Analyte	Average	Maximum	Minimum	Units
Sodium	160	180	120	g/L
Nitrate	110	200	29	g/L
Free Hydroxide	49	88	7.6	g/L
Nitrite	28	64	6.3	g/L
Carbonate	17	45	3.2	g/L
Aluminum	11	26	1.3	g/L
TOC	5.3	78	0.49	g/L
Fluorine	3.6	14	0.10	g/L
Phosphate	3.3	13	0.24	g/L
Oxalate	3.1	14	0.34	g/L
Sulfur	2.8	8.6	0.81	g/L
Chlorine	1.7	4.2	0.46	g/L
Potassium	1.2	6.5	0.17	g/L
Silicon	0.66	3.7	0.047	g/L

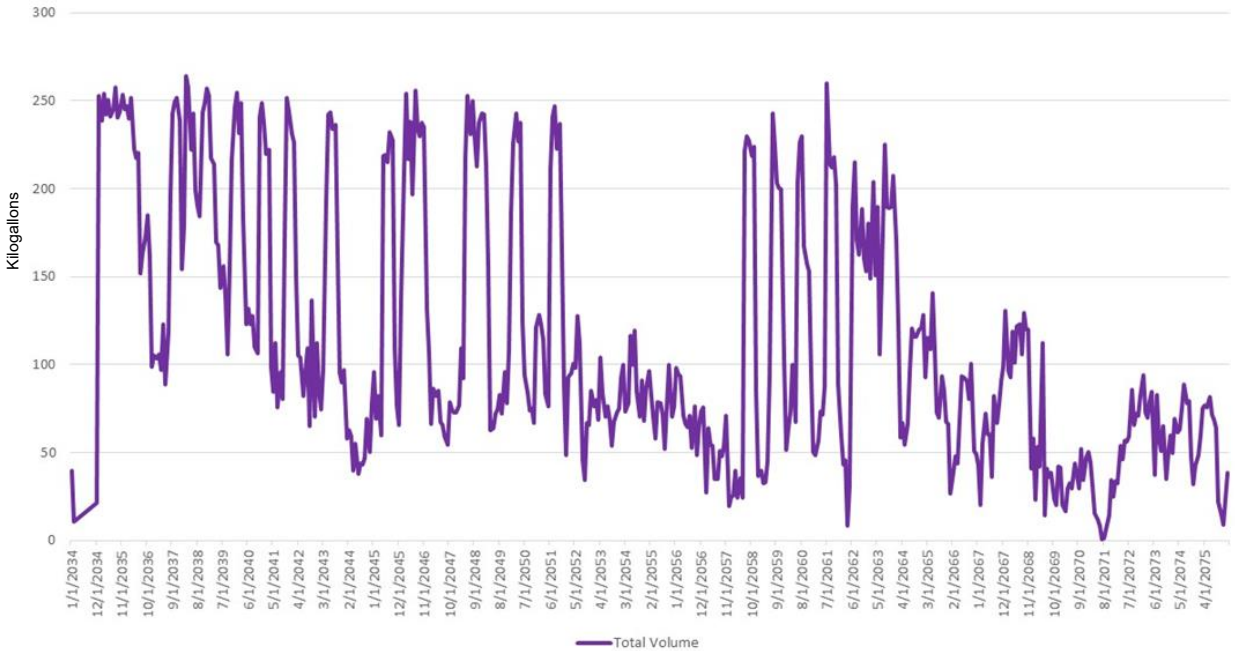
Source: Scenario 1B of ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.
TOC = total organic carbon.

The "Adjusted Amount" in Table 1.3-2 adjusts the ^{90}Sr amount to account for a decontamination factor (DF) of 100 assumed for the ^{90}Sr absorption in TSCR for non-complexant waste for the System Plan Scenario 1B feed vector. Complexant waste is assumed to have a lower DF for strontium, so the adjustment is based only on its removal from non-complexant waste for LAW supplemental treatment. This study assumes complexant waste could be sent to the WTP LAW melter if it is not compatible with grouting.

Table 1.3-2. Radionuclides in Pretreated Low-Activity Waste Specified for Supplemental Treatment in System Plan (Rev. 9) Scenario 1B

Radionuclide	Total Amount in Supplemental LAW Feed[a] (Ci)	Adjusted Amount (Ci)	Radionuclide	Total Amount in Supplemental LAW Feed[a] (Ci)	Adjusted Amount (Ci)
^{90}Sr	300,000	3,000	^{234}U	5.3	5.3
^{151}Sm	51,000	51,000	^{238}U	5.3	5.3
^{99}Tc	12,000	12,000	^{242}Cm	4.6	4.6
^{63}Ni	5,900	5,900	^{237}Np	4.4	4.4
^{137}Cs	1,500	1,500	^{244}Cm	3.3	3.3
^{241}Am	1,300	1,300	^{60}Co	2.2	2.2
^{93}Zr	460	460	^{152}Eu	2.1	2.1
^{93m}Nb	460	460	^{155}Eu	2.0	2.0
^{14}C	350	350	^{243}Am	0.63	0.63
^{239}Pu	320	320	^{231}Pa	0.48	0.48
^{79}Se	220	220	^{227}Ac	0.32	0.32
^{59}Ni	110	110	^{125}Sb	0.24	0.24
^{126}Sn	95	95	^{243}Cm	0.24	0.24
^{113m}Cd	89	89	^{235}U	0.22	0.22
^{241}Pu	88	88	^{236}U	0.14	0.14
^{240}Pu	68	68	^{232}U	0.13	0.13
^{3}H	48	48	^{228}Ra	0.047	0.047
^{154}Eu	26	26	^{232}Th	0.039	0.039
^{233}U	15	15	^{242}Pu	0.031	0.031
^{129}I	12	12	^{229}Th	0.027	0.027
^{238}Pu	12	12	^{226}Ra	0.00015	0.00015

[a] ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.
LAW = low-activity waste.



Source: ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

Figure 1.3-2. Monthly Volume Fed to Supplemental Low-Activity Waste Treatment (kilogallons)

Although no adjustments were made in Table 1.3-2 for ^{151}Sm, the concentration is expected to be significantly lower in concentration because the amount reported in the feed vector does not accurately account for its low solubility. Similarly, removal of the plutonium and neptunium isotopes from non-complexant waste is not adjusted in Table 1.3-2, even though CST is known to remove over 50% of each (PNNL-28783, *Dead-End Filtration and Crystalline Silicotitanate Cesium Ion Exchange with Hanford Tank Waste AW-102*; PNNL-27706, *Cesium Ion Exchange Testing Using Crystalline Silicotitanate with Hanford Tank Waste 241-AP-107*; and PNNL-30712, *Ion Exchange Processing of AP-105 Hanford Tank Waste through Crystalline Silicotitanate in a Staged 2- then 3-Column System*). Removal of these isotopes would not change the NRC waste classification of the liquid. Additional details for the feed vector are described in Volume II, Appendix B.

1.3.1.2 Mission Length and Required Supplemental Low-Activity Waste Treatment Capacity

As shown in Figure 1.3-2, per System Plan Scenario 1B (ORP-11242, Rev. 9), the supplemental LAW treatment facility begins operating in 2034 and operates through 2075. As with the volume and composition, the mission duration for the supplemental LAW treatment facility will be impacted by the assumptions made for WTP HLW Vitrification Facility processing and tank sequencing. In most scenarios, the WTP HLW Vitrification Facility mission determines the overall River Protection Project (RPP) mission length, with little impact from the supplemental LAW treatment capability. However, these scenarios assume that the supplemental LAW treatment capacity is set so that the WTP HLW Vitrification Facility mission is not impacted. If supplement LAW treatment capacity is less than the amount needed in a given month, waste processing at the WTP HLW Vitrification Facility will be impacted and the mission length extended. Therefore, the required capacity for the supplemental LAW treatment is based on the maximum amount to be processed in a month during the overall RPP mission.

The date for HLW melter startup is set at December 31, 2033, by Consent Decree (2022). The ramp-up rate of the HLW melters can vary between modeling runs due to several factors, so the exact need date for the LAW supplemental treatment capability varies accordingly. In the model run performed for this report (MR-50713, *NDAA LAWST Modeling Study*), the HLW melter begins operation at 57% of rated capacity and ramps to 100% of rated capacity at the end of 2038.

Setting the capacity of the supplemental LAW facility at the monthly maximum will result in operation of the facility at less than design capacity for most of the supplemental LAW mission. As a result, supplemental LAW processes that can maintain operational efficiency even at reduced capacity or that can be easily started and stopped would be beneficial.

Note that delaying the start of supplemental LAW treatment can increase the required capacity of supplemental LAW treatment and delays the WTP HLW Vitrification Facility mission since the WTP HLW Vitrification Facility will run at reduced capacity until the supplemental LAW treatment facility is started. Other aspects of the tank waste treatment program, such as SST retrievals, could also be impacted by delays in supplemental LAW treatment. Figure 1.3-3 provides a linkage of the potential mission completion dates with and without LAW supplemental treatment and as a function of the LAW supplemental facility start-up dates. System planning modeling efforts, somewhat analogous to those employed by DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC&WM EIS) (and associated Reader's Guide and Summary), indicate that without LAW supplemental treatment, the tank waste mission could potentially extend well beyond 2090, facilitating the potential need to replace the WTP complex at least once. Figure 1.3-3 also depicts an opportunity for an "Early Start" approach, in which alternatives entailing off-site disposal could allow for supplemental LAW treatment to begin as early as 2027.

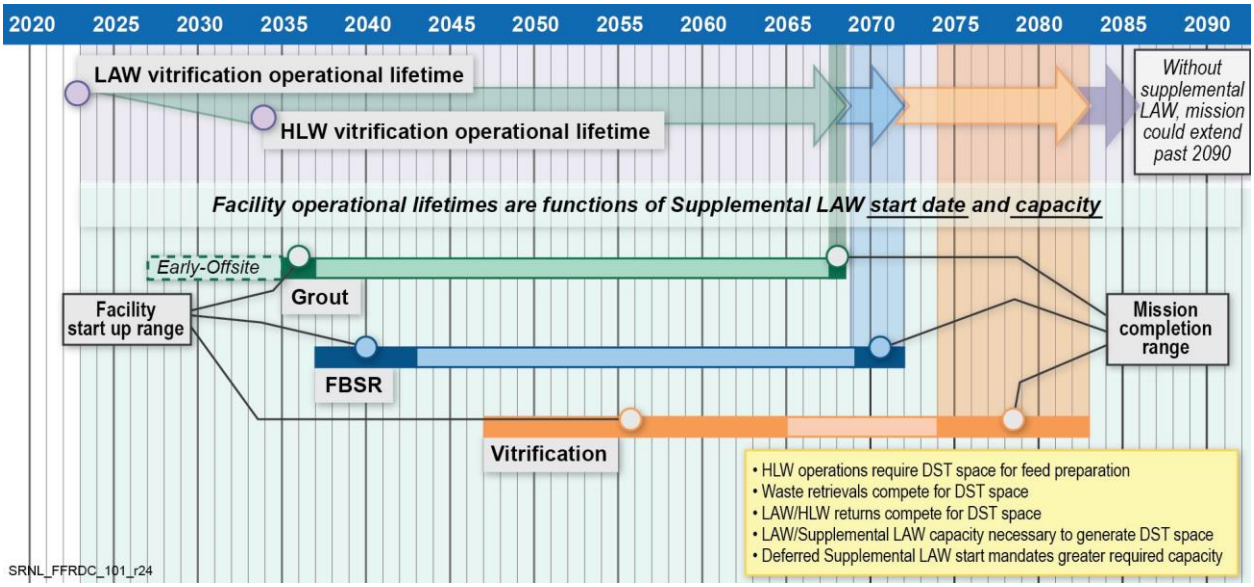
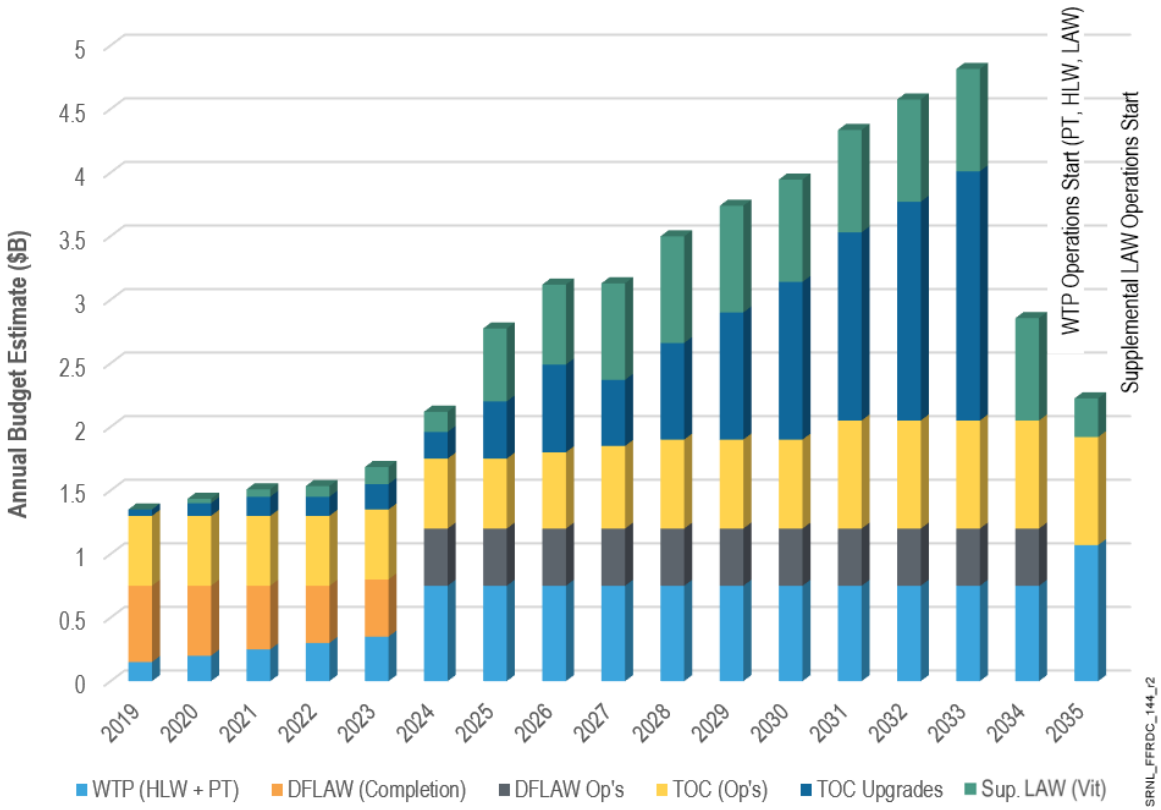


Figure 1.3-3. Relationship Between Low-Activity Waste Supplemental Treatment Start Date and Projected Tank Waste Mission Completion Date

As previously described, the tank waste cleanup mission is paced by vitrification of the tank waste sludge portion via the WTP HLW Vitrification Facility. HLW vitrification requires feed preparation to increase solids content and remove a large fraction of the soluble sodium salts – that volume is delivered to the WTP LAW Vitrification Facility and to LAW supplemental treatment for processing and disposition. HLW feed preparation requires processing capability and DST space. DST space is also required to consolidate and store the incoming waste volume from SST retrievals. Further, space is required to store HLW vitrification effluent and integrate that volume via feed preparation and LAW processing. All of these actions must be integrated with production capability and rates. The focus of LAW supplemental treatment is to increase the work-off rate of the tank waste volume to support the overall retrieval/storage/preparation system capacity – allowing HLW vitrification to effectively pace the RPP clean-up mission. Per Figure 1.3-3, LAW supplemental treatment operations are assumed to be unconstrained by either feed preparation or funding.

The previous NDAA report (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*) provided the matching unconstrained near-term funding necessary to provide this suite of capabilities, as projected in 2018 – as reproduced in Figure 1.3-4. The confluence of capital projects, specifically the completion of WTP and Hanford tank farms upgrades, in addition to LAW supplemental treatment as vitrification, when added to the expected operations cost for DFLAW processing, represent a risk to successful LAW supplemental treatment.

Figure 1.3-3 illustrates this point as the timeline links the projected start-up dates for various LAW supplemental treatment processes, with the concordant impact to the overall processing mission schedule. Based on the modeling results from previous work (and consistent with the results summarized in the TC&WM EIS [DOE/EIS-0391]), HLW vitrification, when operational, is significantly limited without the supporting capability provided by LAW supplemental treatment. A rough assessment indicates that the WTP HLW Vitrification Facility will be limited to one-half throughput—in other words, every 2 years of HLW facility operations without LAW supplemental treatment adds 1 year to the overall mission (MR-50713). Constraining the start-up dates of LAW supplemental treatment (as a function of project cost and schedule) will therefore significantly impact the completion date for waste treatment.



Source: Figure 1 of SRNL-RP-2018-00687, 2019, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*, Savannah River National Laboratory, Aiken, South Carolina.

Figure 1.3-4. Unconstrained Funding Profile (Unescalated) Reflecting the Major Cost Elements Leading to Full Hanford Mission Operations

As the LAW supplemental treatment dates are a function of facility cost, higher facility costs carry the risk of a later starting date (and larger range thereof), more HLW vitrification years at lower capacity, and a longer total mission duration with concordantly higher cost. Conversely, if LAW supplemental treatment can be facilitated without large capital projects, start dates prior to 2035 would allow use of available DST space for feed preparation (LAW and HLW) and to support retrievals.

A Hanford tank waste treatment mission that extends until 2075 or beyond requires the treatment facilities to be built for the expected mission length, and also requires an extended life for the existing facilities and systems that will support the mission. The waste storage SSTs and some of the DSTs have already exceeded their design life, and the risk of additional tank leaks is a significant concern given the length of time needed to complete Hanford tank waste treatment.

1.3.2 Hanford Tank Leaks

Some of the waste storage tanks at Hanford have leaked in the past, and the risk of future emerging additional leaking tanks exists given the expected duration of the tank waste treatment mission. This analysis recognizes this condition but does not attempt to predict or model the timing or extent of future leaks, although removing waste sooner would reduce the probability of a tank leak. The Hanford Site has extensive surveillance and monitoring protocols and other tank integrity programs in compliance with DOE M 435.1-1, *Radioactive Waste Management Manual*, to monitor the status of the tanks and reduce the risk of future leaks; these programs are described in RPP-7574, *Double-Shell Tank Integrity Program Plan*, and RPP-PLAN-60765, *Single-Shell Tank Integrity Program Plan.*

Tank Farms and Leaks

The Hanford waste tank farms (groups of tanks) were constructed to store waste generated from reprocessing spent nuclear fuel to recover plutonium, with the first tank farms entering service in 1944. These tanks are typically 75 ft in diameter, with varying height to achieve 530, 758, or 1,000 kilogallon capacity,[4] and are buried 6–8 ft below grade (CNWRA-97-001, *Hanford Tank Waste Remediation System Familiarization Report*). Initially, single-walled (or single-shelled) tanks (technically, a concrete vault with a carbon steel liner) were constructed with a total of 149 SSTs entering service during the 1940s, 1950s, and 1960s. In the late 1960s, tank construction shifted to the use of double-walled (or double-shelled) tanks, with 28 tanks completed between 1970 and 1986 (PNNL-13605, *A Short History of Hanford Waste Generation, Storage, and Release*). Many of the SSTs developed leak sites or are assumed to have leak sites, as shown in Table 1.3-3. Note that a leak site does not imply an active leak. The tank waste level could be below the leak site or interim stabilization methods (described below) taken to mitigate leaks have prevented or mitigated leaks from the leak site. One of the oldest DSTs, Tank AY-102, developed a leak in the interior tank (waste was noted in the annular space between the inner and outer tanks).

Table 1.3-3. Hanford Tank Farms

Farm	Years built	Number of tanks	Tank type	Quadrant	Assumed or Confirmed Past Leakers	Comments
T	1943-1944	16	SST	NW	5	
TX	1947-1948	18	SST	NW	6	
TY	1951-1952	6	SST	NW	5	
B	1943-1944	16	SST	NE	11	
BX	1946-1947	12	SST	NE	5	
BY	1948-1949	12	SST	NE	5	
C	1943-1944	16	SST	SE	6	Retrieval complete – awaiting closure
U	1943-1944	16	SST	SW	4	
S	1950-1951	12	SST	SW	0	Tank S-122 retrieval complete
SX	1953-1955	15	SST	SW	8	
SY	1974-1976	3	DST	SW	0	
A	1953-1955	6	SST	SE	2	
AX	1963-1965	4	SST	SE	0	Retrievals in progress. Tanks AX-102 and AX-104 retrievals complete, AX-103 retrieval in progress, AX-101 retrieval scheduled to begin January 2023.
AY	1968-1970	2	DST	SE	1[a]	(Tank AY-102 retrieved, awaiting closure)
AW	1976-1980	6	DST	SE	0	
AZ	1970-1974	2	DST	SE	0	
AN	1977-1980	7	DST	SE	0	
AP	1982-1986	8	DST	SE	0	Feed tanks for DFLAW

Source: HNF-EP-0182, 2022, *Waste Tank Summary Report for Month Ending November 30, 2022*, Rev. 419, Washington River Protection Solutions, LLC, Richland, Washington.

[a] Tank AY-102 – Primary tank leak into the annulus.

DFLAW = direct-feed low-activity waste.
DST = double-shell tank.
NE = northeast.
NW = northwest.
SE = southeast.
SST = single-shell tank.
SW = southwest.

[4] Four smaller tanks (200-series, ~55,000 gallons) were built along with the 12 larger tanks (100-series) in the initial tank farms (B, C, T, and U Farms). These small tanks are included in the tank counts.

The first known tank leak dated to the 1950s, with stress corrosion cracking along the weld lines indicated as the probable cause for most of the leaks identified (CNWRA-97-001).

Past Leak Mitigation Measures

Leak mitigation efforts at Hanford focused on removal of free supernatant liquid from the tanks. A campaign known as the Interim Stabilization Program was conducted to remove pumpable liquids, to reduce motive force and increase viscosity of the waste to reduce the risk of leaking. Criteria were established to be met for completing removal from the tanks.[5] To accomplish this campaign, a "well" was bored into the solids in the tank waste, and liquids were pumped from the well until as much liquid in the tank was removed as practical. This process was performed for all SSTs, not just the tanks known to be leaking. This process was deemed impractical for selected tanks; so instead, leak mitigation used additions of cement (Tank BY-105) or diatomaceous earth (Tanks BX-102, SX-113, TX-116, TX-117, TY-106, and U-104) to bind any free liquid in the tanks (LA-UR-96-3860, *Hanford Tank Chemical and Radionuclide Inventories: HDW Model Rev. 4*). The SSTs were then operationally isolated, with all transfer paths in and out of the tanks removed and blind flanged (sealed).

For the one known leak in a DST (Tank AY-102), the mitigation method was removal of the waste from the tank.

Risk and Impact of Tank Leaks

Single-Shell Tanks

Leak rates from SSTs have been minimized by removal or stabilization of free liquids (interim stabilization) in these tanks. However, these measures have not completely removed the potential for future leaks from residual liquids. Thus, continued storage of waste in these tanks has the potential to result in additional leaks of radionuclides and hazardous chemicals into the soil at the Hanford Site, and this risk increases as the tanks continue to age. This risk is known and captured in the programmatic risks for the RPP mission.

Retrieval operations to remove waste from a tank typically consist of sluicing the waste with water (or supernatant liquid from a DST) to dissolve salts and suspend solids, and then extracting the pumpable slurry. This process adds liquids back to the SSTs to mobilize the waste for transfer and could result in leakage of that added liquid from the tanks through existing leak locations. Methods to mobilize the waste without the addition of large amounts of liquid were demonstrated during C Farm retrievals, and methods to remove the waste using mining techniques that do not add water to the tank are currently being researched. This risk is known and captured in the programmatic risks for the RPP mission.

Thus, additional leaks from SSTs would add to the inventory of radionuclides and hazardous chemicals in the Hanford soil and groundwater plumes, but would have little programmatic impact on the tank waste immobilization program because (1) mitigation measures to minimize the risk of leaks from SSTs have been performed on all SSTs, (2) methods to retrieve the tanks have been developed to minimize leaks from retrieving the tanks and continued development of the tank retrieval methods is in progress, and (3) the SSTs are not used as part of the staging process for any other tanks (all SSTs are retrieved into a DST) and no material is transferred through a SST for transfer routing, thus no loss of programmatic function occurs.

[5] The Interim Stabilization Program criteria were met if: (1) less than 50,000 gallons of drainable interstitial liquids remained; (2) 5,000 gallons of supernatant liquid remained; and (3) less than 0.05 gallons per minute of liquid flow if jet pumping was used. DOE successfully completed the Interim Stabilization Program in 2010.

Acceleration of the retrieval and immobilization process for the waste stored in SSTs would minimize the risk of additional leaks. Acceleration not only requires available DST space to receive the retrieved waste, but also requires a significant investment in tank farms infrastructure. The infrastructure investments include the equipment needed to sluice the waste from the tanks and the piping systems to transfer the sluiced waste to the DSTs. For SSTs that are remote from the DST farms, additional facilities to allow efficient reuse of the sluicing supernatant liquids and efficient transfer to the DSTs are needed.

Double-Shell Tanks

As discussed above, one DST has developed leaks, Tank AY-102. These leaks occurred on the tank bottom and required the entire contents of the tank to be transferred to mitigate the leak. The Tank AY-102 leak resulted in material in the annulus of the DST, with no release to the ground. Tank AY-102 had been identified as the feed tank for the WTP HLW Vitrification Facility, and extensive characterization of the waste in the tank had been conducted. The loss of this DST required the WTP project to rework the feed staging arrangements and the work performed to evaluate processing the assembled batch. In addition, the material in Tank AY-102 was transferred to the AP Farm and required adjustments to the operational plans for the AP Farm tanks.

While a leak in a DST would typically not result in a release to the soil since the leak would be captured by the secondary tank, the programmatic impact of a DST leak is much larger than a leak in an SST. Assuming the leak requires the tank to be emptied (similar to Tank AY-102), the leak results in loss of function of two DSTs (at least temporarily), with the leaking tank being unusable and the tank(s) that received the waste potentially being full. Depending on how the tanks were planned for use, the programmatic issue could be greater than just loss of storage space. For example, Tank AP-106 was designated as the tank to receive pretreated supernatant liquid from the TSCR system for staging feed to LAW vitrification during DFLAW processing. Since the tank contained unprocessed supernatant liquid, an extensive process was used to empty the tank to support DFLAW feed. A leak in Tank AP-106 would require a new DST to undergo the cleaning process, would delay the DFLAW program much longer than a leak in other DSTs, and would create additional waste from the cleaning process.

Failures of selected DSTs may have little to no impact on the overall immobilization program if the tank failure does not prevent continued operations with the other DSTs except for the loss of operational flexibility, as described above, and potential diversion of funds and resources that could impact removal and treatment schedules. As an example, the leak in Tank AY-102 has not resulted in delays to the immobilization program. Full support of expected WTP operations is expected from the tank farms even with the loss of the tank and as demonstrated by the current integrated flowsheet models, which take into account the loss of Tank AY-102. Failures of a tank with a dedicated function, such as Tank AP-106, could result in a 1- to 3-year delay to repurpose other tanks for that function.

As with the SSTs, acceleration of the RPP mission would reduce the risk of leaks developing in the DSTs prior to mission completion. Unlike the SSTs, the DSTs have a programmatic role in the overall RPP, and development of leaks in other tanks could require significant changes to the planned execution of the RPP. Note that the risk is recognized by the DOE Office of River Protection (ORP) and Hanford Site contractors and is part of the existing risk registers for tank waste treatment.

The failure of Tank AY-102 was attributed to pitting corrosion resulting from reactions with chemicals in the tank waste (Follett 2018). In response, ORP conducted an evaluation of the extent of condition and adopted measures to minimize the risk of similar leaks in the remaining DSTs.

Structural Failure

The risk of a structural collapse of a SST or DST tank during the mission, similar to the collapse of the plutonium-uranium extraction (PUREX) tunnel at Hanford, is not considered in this evaluation. As noted above, the Hanford Site has extensive surveillance programs for the waste tanks that should allow early detection of any structural issues and allow for mitigation measures to be taken if signs of imminent structural failure were noted. These inspection protocols were not in place for the PUREX tunnel. These surveillance programs are described in RPP-7574.

Structural integrity of the 149 SSTs was assessed in a 2015 evaluation (RPP-RPT-49994, *Summary Report for the Hanford Single-Shell Tank Structural Analysis of Record – Single-Shell Tank Integrity Project Analysis of Record*), while structural integrity of the DST system was assessed in 2016 (RPP-RPT-58441, *Double-Shell Tank System Integrity Assessment Report (DSTAR)*).

2.0 REGULATORY OVERVIEW

Section 3125 of NDAA21 calls for continued analysis of approaches for supplemental treatment of LAW as a follow-on to the analysis required by Section 3134 of NDAA17. Although the focus of the FFRDC follow-on report is technical, NDAA17 Section 3134 requested analysis of "compliance with applicable technical standards" with respect to the approaches for supplemental treatment of LAW evaluated by the FFRDC. Section 3134 of NDAA17 specifically references technical standards promulgated under the following federal statutes:

- *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA)
- *Solid Waste Disposal Act* (commonly referred to as the *Resource Conservation and Recovery Act of 1976* [RCRA])
- *Federal Water Pollution Control Act* (often referred to as the *Clean Water Act of 1972* [CWA])
- *Clean Air Act of 1972* (CAA).

In addition to the regulations listed above, the FFRDC team also examined regulatory requirements associated with the following:

- *Atomic Energy Act of 1954* (AEA), as amended, and thereunder, DOE O 435.1, *Radioactive Waste Management*, and DOE M 435.1-1, *Radioactive Waste Management Manual*
- *National Environmental Policy Act of 1969* (NEPA)
- *Hanford Federal Facility Agreement and Consent Order – Tri-Party Agreement* (TPA) (Ecology et al., 1989)
- Washington State RCRA regulations (e.g., *Washington Administrative Code* [WAC] 173-303, "Dangerous Waste Regulations").[6]

In addition, Tribal Nations have treaty rights, traditional use areas, and other interests at the Hanford Site that are addressed by DOE and Tribal Nations through government-to-government interactions, pursuant to DOE O 144.1, *Department of Energy American Indian Tribal Government Interactions and Policy*.

The FFRDC team analyzed the regulatory aspects of the Hanford supplemental LAW treatment and disposal approaches evaluated in this report. The team also reviewed regulatory information provided in the NDAA17 report (SRNL-RP-2018-00687),[7] and considered additional reports and publications related to Hanford supplemental treatment of LAW that became available following issuance of the previous analysis. These advances and remaining uncertainties are described in further detail in Volume II, Appendix A and Appendix E, respectively. The FFRDC team concluded that the AEA (including DOE O 435.1 and DOE M 435.1-1), the RCRA LDRs, and TPA provisions specifically relating to selection of supplemental treatment for LAW—and in particular their interpretation and implementation by regulators—have the greatest significance for differentiating and selecting among supplemental treatment approaches. Technical implementation of permitting requirements (e.g., under RCRA, CAA, CWA) is not a major differentiator among alternatives; however, it is an important part of the regulatory background. The U.S. Government Accountability Office (GAO) report GAO-22-104365, *Nuclear Waste Disposal: Actions Needed to Enable DOE Decision That Could Save Tens of Billions of Dollars*, on Hanford tank waste summarizes how each of these elements of the legal framework applies to Hanford LAW requiring supplemental treatment:

- ***Atomic Energy Act of 1954*, as amended**, authorizes DOE to regulate the radioactive component of mixed HLW.

[6] Additional information is provided in Ecology 96-401, *Differences Between Washington State and Federal Rules--Highlights.*

[7] Regulatory issues addressed in SRNL-RP-2018-00687 (Section 2.5, page 30) are discussed in Volume II, Appendix I.

- ***Resource Conservation and Recovery Act of 1976*, as amended**, governs the treatment, storage, and disposal of the hazardous waste component of mixed waste. EPA has authorized the Washington State Department of Ecology (Ecology) to administer its own hazardous waste regulatory program in lieu of the federal program.
- **DOE O 435.1 and DOE M 435.1-1**, issued in July 1999 and subsequently revised, set forth procedures for the management of DOE's radioactive wastes in a manner that is protective of worker and public health and safety and the environment. Under the manual associated with this Order, DOE has two processes for determining that waste can be managed as non-HLW, which is less expensive to manage and dispose of than HLW.
- ***Hanford Federal Facility Agreement and Consent Order – Tri-Party Agreement*** **(TPA)** (Ecology et al., 1989) is an agreement among DOE, EPA, and Ecology that lays out, among other topics, a process and a series of legally enforceable milestones for selecting a technology and constructing facilities to treat the supplemental LAW.
- The **Consent Decree (2010), as amended**, was established as a result of litigation brought against DOE by Ecology for missing certain TPA milestones. This judicially enforceable Consent Decree establishes, among other items, specific cleanup milestones for retrieval of waste from certain specified tanks and the commissioning and operation of the WTP.

The FFRDC team did not draw conclusions as to the likelihood that any given approach for supplemental treatment would be acceptable to or approved by Ecology. Instead, the team viewed regulatory acceptance as an uncertainty, one that could be resolved in a number of different ways, including by negotiation, legislative or agency action, or judicial decision.

Management of the low-activity fraction of tank waste at different DOE facilities is accomplished under different regulatory frameworks. For example, at SRS, tank waste is treated, and the low-activity fraction is disposed of at the Saltstone Facility, which is regulated under the CWA, through a wastewater operating permit. As discussed below, Hanford tank waste is regulated under RCRA, and consequently the CWA permitting approach used at SRS is not applicable.

The assessment of the key regulatory issues presented by the LAW supplemental treatment approaches evaluated by the FFRDC team follows. Supplemental regulatory background and information are provided in Volume II, Appendix I.

Regulatory Challenges for Selection of a Non-Vitrification Approach for Supplemental Treatment of Hanford Low-Activity Waste

Ecology's position is that all Hanford tank waste, including LAW, that is intended for disposal at Hanford, is required to be vitrified or alternatively must obtain a variance under RCRA prior to disposal.[8] Ecology told the FFRDC team that compliant disposal of non-vitrified LAW from Hanford tanks could not take place anywhere on the Hanford Site or in the state.[9] However, with respect to out-of-state disposition of LAW, Ecology states that "grouting of tank waste may be appropriate depending on the disposal facility's geology and waste acceptance criteria" (Volume II, Appendix J).

[8] Ecology notes that disposal (or treatment) of tank waste in any form onsite at Hanford would require Ecology's approval through the RCRA permitting process, with "significant public input from stakeholders and the impacted communities, including tribal nations." The FFRDC team provided questions to Ecology regarding Ecology's understanding of the legal and regulatory context for selection of supplemental LAW treatment capacity. Ecology provided a detailed response to the questions, which is provided in its entirety as Volume II, Appendix J.

[9] "Ecology notes that tank waste solidified into a grout matrix will not be able to meet waste acceptance criteria at any landfill disposal facility in the state of Washington, whether on or off the Hanford Site" (Volume II, Appendix J).

DOE conducted the initial phases of a DOE pilot research and development (R&D) program at Hanford, the Test Bed Initiative (TBI).[10] The TBI pilot included off-site commercial grout treatment and disposal at a licensed out-of-state commercial land disposal facility of a small quantity (3 gallons [11.4 L]) of tank waste that DOE has determined is not HLW under the AEA because the waste meets the criteria for waste incidental to reprocessing (WIR), pursuant to DOE O 435.1.[11] The LAW used in the 3-gallon TBI demonstration was grouted in Washington State at the Perma-Fix Northwest, Inc. (Perma-Fix Northwest) treatment facility, located near the Hanford Site, and was transported to and disposed of at the Waste Control Specialists, LLC commercial mixed waste disposal site in Andrews, Texas. Ecology has nonetheless expressed general concerns about the off-site disposition of Hanford tank waste. Of greatest concern is the prospect that non-vitrified waste deemed unacceptable for out-of-state disposal might be returned to or unable to be shipped from Hanford. Ecology's concern about "orphaned" tank waste also extends to any LAW that would be treated on the Hanford Site by a method other than vitrification (Volume II, Appendix J).

DOE asserts that vitrification is not required for LAW for which DOE determines the radioactive component is not HLW and not to be treated at WTP. Where, for example, DOE has made a WIR determination that the LAW used in the TBI demonstration is not HLW, the Department contends that it is lawful to use a non-vitrification treatment method, such as grout, either onsite at Hanford or at an off-site commercial treatment facility, and/or to dispose of the grouted LAW either onsite at the Hanford IDF or offsite at a commercial land disposal facility (GAO-22-104365).

Key legal instruments that address the issue of vitrification versus alternative treatment technologies for Hanford LAW include the TPA (Ecology et al., 1989), RCRA, the state's EPA-authorized RCRA program, AEA, and NEPA,[12] and other regulations, DOE Orders, and guidance under the foregoing.[13] The discussion that follows provides context and a brief overview of the key aspects of the regulations that may impact alternatives selection (additional discussion is provided in Volume II, Appendix I).

[10] The 3-gallon TBI was conducted by DOE as a RCRA treatability study pursuant to WAC 173-303-071(3)(r) and (s): 40 CFR 261.4(e) and (f).

[11] Based on the positive results of the 3-gallon TBI, DOE and Ecology had begun planning for another TBI action, which would involve off-site grout treatment and out-of-state commercial land disposal with respect to another 2,000 gallons of Hanford tank waste that DOE determines to be WIR. DOE had submitted a request for a RCRA research, development, and demonstration (RD&D) permit to Ecology for the 2,000-gallon TBI; however, DOE subsequently rescinded its permit request. Accordingly, the 2,000-gallon TBI is no longer formally under consideration, although Ecology has indicated support for the 2,000-gallon TBI and that the permit process for the demonstration will restart (see Volume II, Appendix J).

[12] Although not discussed in detail in this report, NEPA is a federal statute that requires federal agencies to assess the environmental effects of their proposed actions prior to making decisions. NEPA has been a key part of the framework for decision-making on remediation at Hanford, including with respect to disposition of tank waste, in part through preparation of detailed analysis of tank waste alternatives in EISs (e.g., TC&WM EIS [DOE/EIS-0391]). The TC&WM EIS specifically evaluates alternative supplemental treatment options for Hanford LAW, including both vitrification and non-vitrification alternatives.

[13] Additional laws and regulations relevant to supplemental treatment of LAW at Hanford, including the CWA, CAA, and NEPA, are discussed in Volume II, Appendix I.

Hanford Tri-Party Agreement

The Hanford TPA is a comprehensive cleanup agreement among DOE, Ecology, and EPA, who entered into it pursuant to (variously) CERCLA, RCRA, and the Washington Hazardous Waste Management Act.[14] The parties signed the TPA initially in 1989, and it is periodically updated based on negotiated changes to process and mission direction. Among other actions, the TPA requires that remediation of the Hanford tanks, including disposition of their contents, be conducted under RCRA, rather than CERCLA. Washington State, specifically Ecology, is the entity authorized by EPA to implement RCRA in the state, using the state's RCRA regulations in lieu of EPA's.[15] The TPA Action Plan establishes milestones for DOE completion of remediation tasks agreed to by the parties, including retrieval and disposition of tank wastes.[16] In addition to regulatory oversight by Ecology, implementation of TPA milestones for the Hanford tanks is being overseen by a federal district court in Washington State with continuing jurisdiction, pursuant to a Consent Decree.[17]

The TPA specifically mentions supplemental treatment of LAW in the Action Plan, which contains ambiguous milestones with respect LAW treatment. Milestone M-062-00 addresses pretreatment and vitrification of Hanford HLW and LAW. Milestone M-062-45, agreed to more recently, specifically addresses selection of *supplemental treatment* for LAW.

Milestone M-062-45 established a deadline for selection of a supplemental treatment method for LAW, considering supplemental treatment options including a second LAW vitrification facility.[18]

[14] The TPA (Part One, Article III) states that the general purposes of the agreement are to:
"A. Ensure that the environmental impacts associated with past and present activities at the Hanford Site are thoroughly investigated and appropriate response action taken as necessary to protect the public health, welfare and the environment;
B. Provide a framework for permitting TSD [treatment, storage, and disposal] Units, promote an orderly, effective investigation and cleanup of contamination at the Hanford Site, and avoid litigation between the Parties;
C. Ensure compliance with RCRA and the *Washington Hazardous Waste Management Act* (HWMA) (Chapter 70A.300 RCW) for TSD Units including requirements covering permitting, compliance, closure, and post-closure care.
D. Establish a procedural framework and schedule for developing, prioritizing, implementing and monitoring appropriate response actions at the Hanford Site in accordance with CERCLA, the National Contingency Plan (NCP), 40 CFR 300, Superfund guidance and policy, RCRA, and RCRA guidance and policy;
E. Facilitate cooperation, exchange of information and the coordinated participation of the Parties in such actions; and
F. Minimize the duplication of analysis and documentation."

[15] TPA (2021) identifies Ecology as the lead regulatory agency for tank remediation and indicates that such remediation will be conducted under RCRA.
The TPA views remediation undertaken under either CERCLA or RCRA as satisfying the requirements of both statutes (see Ecology et al. [1989] Article VIII, Paragraph 17). Although cleanup under RCRA is regarded as equivalent to that undertaken under CERCLA, as a practical matter, there may be differences in decisional processes – and outcomes – depending on which statute governs the remedial action and which party is in the lead. For instance, CERCLA is implemented by EPA, with input from states and EPA implementation of more stringent state standards (including state RCRA standards) *if* EPA determines that such state standards are "applicable" or "relevant and appropriate." RCRA requirements including those for remediation, on the other hand, are implemented by states authorized by EPA to carry out those requirements, including Washington State, in accordance with such state requirements, which may be more stringent than and/or somewhat different from EPA's requirements. Remediation under RCRA is managed by the authorized state under its RCRA permit authority. Once a state is RCRA-authorized to implement a given set of RCRA requirements, such as permitting, EPA retains residual RCRA enforcement authority, but does not generally intervene in the state's implementation of the state-authorized portion of the RCRA program. EPA directly implements RCRA program requirements in states that lack authorization to implement those particular RCRA requirements and, as a practical matter, only rarely initiates enforcement of the federal RCRA regulations in an authorized state.

[16] The TPA Action Plan (TPA, 2022) establishes "the overall plan for hazardous waste permitting, meeting closure and post-closure requirements, and remedial action under RCRA and CERCLA and the Washington State Hazardous Waste Management Act." The Action Plan contains a work schedule (milestones) that sets priorities.

[17] Consent Decree (2010), as amended by Consent Decrees (2016a, 2016b, 2018, and 2022).

[18] Item 3 of Milestone M-062-45 requires "Supplemental treatment selection (a one-time selection to be made not later than April 30, 2015) and [negotiation of] milestones, which must be consistent with M-062-00 as established by M-062-45 item #5. A 2nd LAW Vitrification Facility must be considered as one of the options."

While M-062-00 addresses vitrification, M-062-45 introduces the possibility that a different supplemental treatment may be selected. DOE and Ecology do not agree on what is required – or allowed – under the TPA for supplemental treatment of LAW and are engaged in a dispute resolution process under Article VIII of the TPA to resolve the matter.[19] Independent of but parallel to the TPA selection process, Congress enacted NDAA17 Section 3134, and subsequently NDAA21 Section 3125, to help facilitate an informed decision selecting the approach for supplemental treatment for Hanford LAW. The NDAA provisions task the FFRDC with assessing supplemental treatment approaches for LAW—specifically including vitrification, FBSR, and grout—and with developing a decision framework for use by decision-makers in selecting among potential treatment approaches.

A decision on the supplemental LAW treatment alternative will require negotiation of additional milestones to be added to the TPA for any treatment alternative. The TPA provides a negotiation vehicle for issues such as supplemental LAW treatment selection. Agreements on approach and priorities made within the TPA framework are intended to establish a basis for permitting activities.

Determining RCRA Treatment Standards Applicable to Mixed Waste Destined for Land Disposal

The kind of supplemental treatment that is required—or allowed—for the Hanford LAW depends substantially on the requirements of, and the scope of regulatory authority and regulatory discretion under, both RCRA and the AEA with respect to mixed wastes. Hanford tank waste is "mixed waste" – a mixture of both chemically hazardous and radioactive waste, and as such is subject to both RCRA and the AEA. In Washington State, Ecology rather than EPA is in charge of implementing the RCRA program, including regulation of mixed waste, permitting of mixed waste treatment, storage and disposal facilities, and implementation of the LDR treatment standards (40 CFR 268, "Land Disposal Restrictions") for mixed waste, by incorporating by reference EPA's LDR program in WAC 173-303-140(2)(a).[20]

Among the key regulatory questions relevant to the issue of allowable supplemental LAW treatment under RCRA are: whether the Hanford LAW is mixed *HLW* for purposes of implementing the RCRA LDR regulations; and whether Ecology is authorized to determine that the RCRA LDR standard for mixed HLW applies to LAW when DOE has determined under the AEA that the radioactive portion[21] of the waste is not HLW, or in the absence of a DOE determination characterizing the radioactive portion of the mixed waste. As discussed below, DOE asserts that under the AEA it is DOE that is authorized to determine whether the radioactive portion of tank waste is HLW – or not-HLW. Ecology contends that, pursuant to its RCRA authority, it is authorized to determine that the tank waste qualifies as high-level mixed waste for purposes of the state's implementation of the RCRA LDR regulations (Volume II, Appendix J).

[19] With the agreement of all parties, the TPA could be amended, for example, to clarify the intent with respect to supplemental treatment of LAW and/or to specify use of a particular supplemental treatment method for LAW at Hanford.

[20] Under RCRA, EPA can authorize a state to implement the RCRA program using its own regulations, provided the state's regulatory program is no less stringent than, consistent with, and equivalent to the federal RCRA program; state programs can be more stringent than the EPA program. EPA generally gives authorized states broad discretion to implement RCRA program requirements. However, in authorized states, EPA still retains RCRA enforcement authority that it may choose to exercise in appropriate instances.

[21] EPA refers to the radioactive constituents in the mixed waste as the "radioactive portion." DOE characterizes waste and makes a determination as to whether waste is HLW or not after completion of treatment pursuant to DOE O 435.1. At Hanford, the plan is to separate tank waste into a high-activity fraction and a low-activity fraction (i.e., LAW) for separate treatment and disposal. After waste fractions are physically separated and treated, the low-activity fraction of the tank waste may have a different classification (not HLW vs. HLW) than the high-activity fraction of the tank waste.

Mixed waste is dually regulated under both RCRA and the AEA. Under the dual regulatory scheme, EPA—or the RCRA-authorized state—regulates the chemically hazardous portion of mixed waste (only), and DOE regulates the radioactive component of mixed waste (only). EPA recognizes this AEA/RCRA jurisdictional divide, which stems from Section 11(e) of the AEA, RCRA Section 1006(a) and 10 CFR 962, "Byproduct Material." These provisions exempt the radioactive portion of mixed waste from regulation under RCRA.[22]

As EPA states with respect to mixed waste:

> "*RCRA regulates the hazardous waste portion of the [mixed] waste as any other hazardous waste, while the AEA regulates the RCRA-exempt radioactive portion.* If waste is categorized as "mixed waste," the handlers must comply with both AEA and RCRA statutes and regulations, which are usually compatible. In the cases where AEA and RCRA contradict each other, the provisions in Section 1006(a) of RCRA allow the AEA to take precedence over RCRA." [Emphasis added.] (EPA, 2022)

EPA's "Third-Third Rule," which establishes the LDR standards for mixed waste bearing waste numbers D001–D017, requires that specified non-wastewater high-level mixed waste, "Radioactive high-level wastes generated during the reprocessing of fuel rods," falling within D002 and D004-11, be treated by the HLVIT method prior to land disposal (40 CFR 268.40, "Treatment Standards for Hazardous Wastes"). Mixed wastes not meeting this description do not require vitrification, but must meet all LDR standards applicable to the waste. Where there is no specific treatment standard for radioactive mixed waste, the treatment standard for the hazardous waste (as designated by EPA waste code) applies (40 CFR 268.42(d)).[23]

The high-level mixed waste that EPA requires be treated by HLVIT, as specified in the Preamble to the Final Third-Third Rule, is: "*the high-level fraction* of the mixed waste generated during the reprocessing of fuel rods exhibiting the characteristics of corrosivity [D002] and toxicity for metals [D004-D011]" (55 FR 22627, "BDAT Treatment Standards for D001, D004, D005, D006, D007, D008, D009, D010, and D011"). The Preamble emphasizes that vitrification is only necessary for the "high-level fraction" of DOE "high-level waste generated from reprocessing of fuel rods." Following separation of "the low-level radioactive waste fractions from the high-level radioactive waste. *The high-level radioactive portion is then vitrified… By separating high-level and low-level mixed wastes, the amount of high-level waste that may require vitrification treatment can be reduced*" (55 FR 22627, "b. Applicable Technologies"). The Preamble also states that stabilization using grout is acceptable and anticipated treatment for the low-activity fraction of DOE high-level mixed waste. "The performance data indicate that [grout] stabilization provides immobilization of the characteristic metal constituents and radioactive contaminants for this low-level radioactive waste, and that it is possible to stabilize the RCRA hazardous portions to meet the treatment levels for the characteristic metals." The Preamble found a variety of different non-vitrification treatments suitable for treating organic chemicals in the low-activity fraction of DOE high-level mixed waste to meet LDR standards (55 FR 22626-27, "8. Radioactive Mixed Waste").

[22] Section 11(e) of the AEA confers on DOE authority over "byproduct material." Byproduct material, which includes DOE radioactive waste, is excluded from the RCRA definition of solid waste, of which hazardous waste (including mixed waste) is a subcategory. Further, 10 CFR 962, interpreting the RCRA/AEA regulatory interface, defines as RCRA-exempt the radionuclides portion of mixed waste, in respect of mixed waste that DOE owns or produces at DOE facilities and self-regulates under the AEA (52 FR 15940, "Part 962—Byproduct Material"). Accordingly, the radioactive components of DOE's mixed waste are exempt from RCRA regulation and DOE, not EPA or authorized states, has the authority to regulate the radioactive portion of mixed waste at DOE facilities.

[23] Volume II, Appendix C discusses how specific alternatives have been designed to achieve applicable LDR standards. Note that the NDAA17 report (SRNL-RP-2018-00687, pages 265-266) addressed the possibility that pretreated LAW might potentially be recategorized as a wastewater under 40 CFR 262.11(a) and if so, according to the regulations in 40 CFR 268.40, would not be subject to the HLVIT LDR standard; the HLVIT standard only applies to non-wastewaters.

However, as similarly reported by GAO in December 2021, the FFRDC team found that Ecology and DOE are not in agreement about what kind of treatment is mandated—or acceptable—for Hanford LAW to comply with RCRA LDR regulations (GAO-22-104365). Ecology asserts that the state's LDR regulations (which largely mirror EPA's regulations) require *all* tank waste, including LAW, to be treated by the HLVIT method prior to land disposal at Hanford. The state contends that the HLVIT LDR standard "attached" to all tank wastes at Hanford in 1990 when EPA promulgated its LDR standards for mixed wastes.[24] Ecology believes that the HLVIT standard remains attached to the tank waste until the waste either meets the HLVIT standard or a variance has been granted, modifying (or waiving compliance with) the HLVIT standard (Volume II, Appendix J). DOE's view, however, is that – although LAW being processed through the WTP will be vitrified – LAW requiring supplemental treatment that DOE has determined is not HLW can lawfully be stabilized with grout to comply with the LDR requirements; this would include, for example, LAW for which DOE has made a WIR determination pursuant to the AEA under DOE O 435.1. Ecology disagrees, stating that "DOE's issuance of a final WIR Determination does not extinguish the RCRA LDR treatment standard of HLVIT" (Volume II, Appendix J).

Variances from RCRA Land Disposal Restrictions Standards

Variances from RCRA LDR standards such as HLVIT, if the LDR standard is applicable, are potentially available. Washington State's LDR regulations allow for a site-specific treatability variance from otherwise applicable LDR standards, which could be granted by Ecology. A site-specific treatability variance could also be approved by the regulatory authority in another state, if the state is authorized to grant treatability variances.[25] Ecology approved a site-specific treatability variance for Hanford tank waste in 2019. In that instance, Ecology approved a treatability variance sought by DOE for Hanford LAW expected to be processed in the WTP. To ensure compliance with the LDR standards, Ecology would have required sampling of the waste for organics – sampling that DOE believed might endanger workers. Instead of sampling, the approved site-specific treatability variance required vitrification of the waste to address the organics (Schleif, 2019).[26]

Another option for a variance from LDR standards would be to petition for a determination of equivalent treatment, allowing another method of supplemental treatment than vitrification for Hanford LAW. Alternatively, DOE could petition EPA for a national treatability variance allowing another method of supplemental treatment than vitrification for the Hanford LAW.

Disposal of a Non-Vitrified Low-Activity Waste Form in the Hanford Integrated Disposal Facility

Ecology opposes disposal of grouted LAW (as a primary waste form) onsite at the IDF. Ecology contends that, on account of Hanford's geology, disposal of grout-treated LAW in the IDF would cause exceedances of SDWA maximum contaminant levels for some tank waste constituents, potentially threatening groundwater and the Columbia River (Volume II, Appendix J).

[24] Although the Third-Third rule was published in the Federal Register on June 1, 1990, with the treatment standards effective May 8, 1990, radioactive mixed waste was granted a 2-year national capacity variance until May 8, 1992 (40 CFR 268, Appendix VII, Table 1 – Effective Dates of Surface Disposed Wastes, footnote a).

[25] EPA guidance on use of site-specific treatability variances in cleanup indicates that such variances may be justified when properties of the waste at issue are different from properties of the waste on which the treatment standard was based or where the treatment standard was based on best demonstrated available technology that is inappropriate for the waste at issue. The guidance illustrates a number of circumstances encountered in cleanups where approval of such variances may be appropriate. These include, for example, cleanups where bench- or pilot-scale studies indicate that LDR treatment standards cannot be achieved; and sludges placed in surface impoundments prior to the effective date of LDR standards, which have changed composition due to prolonged exposure to natural conditions (Shapiro, 1997).

[26] The 2019 variance would not apply to supplemental LAW options for grout and FBSR evaluated in the NDAA21 follow-on report (this document) because the LAW would not be treated at the WTP.

Based on prior analyses, the FFRDC team believes that disposal of grouted LAW at the IDF may well meet applicable standards for groundwater (based on the performance evaluation in SRNL-RP-2018-00687, Appendix F), although, mitigation measures may be required if modeling projects that future groundwater concentrations may exceed 75% of the maximum contaminant limit for any of these constituents, under Ecology's implementation of RCRA (IDF Permit Condition III.11.I.5.a.ii [Ecology, 2021]). Currently, the permit for the IDF does not allow disposal of a grouted LAW as a primary waste form, although Ecology is in the process of amending the permit to authorize disposal of grouted secondary waste from vitrification of Hanford tank waste.[27]

Out-of-State Treatment and/or Disposal of Hanford Low-Activity Waste

At this time, no significant regulatory barriers under RCRA or the AEA appear to preclude the treatment and disposal of Hanford LAW at out-of-state commercial facilities.[28] Ecology implements the RCRA LDR regulations with respect to Hanford tank waste and for prospective treatment facilities offsite but located in Washington State through its permit authority (e.g., over RCRA facilities, including Perma-Fix Northwest).

Nothing in the RCRA regulations would appear to preclude treatment of mixed tank waste at an out-of-state commercial treatment facility and disposal at an out-of-state commercial disposal facility, provided the off-site facility is licensed to treat the tank waste, and the treated tank waste meets disposal facility waste acceptance criteria and LDR requirements prior to disposal. Off-site commercial treatment in Washington State (at Perma-Fix Northwest), followed by disposal at a commercial disposal facility (Waste Control Specialists in Andrews, Texas) of Hanford tank waste, was successfully accomplished during the 3-gallon (11.4 L) TBI demonstration. Further, if the tank waste coming from Hanford for off-site commercial disposal would not be expected to meet all applicable LDR standards, the out-of-state land disposal facility could petition EPA for a "no migration" variance allowing disposal of Hanford tank waste that does not meet LDR standards.[29]

Ecology is concerned, however, that unvitrified waste leaving the Hanford Site may yet return to Hanford and be "orphaned" there, if for some reason the receiving treatment or disposal facility or its host state find the waste unacceptable once the LAW arrives. Ecology indicates potential support for out-of-state treatment and disposal for as much as 500,000 gallons (1.9 million L) of tank waste that is determined to meet DOE M 435.1-1 WIR requirements under the TBI program, although this program has only dispositioned 3 gallons (11 L) of tank waste to date and is an R&D program separate from treatment of LAW. Ecology has indicated that enforceable agreements with potential off-site facilities will be required, guaranteeing that tank waste leaving the Hanford Site for treatment and/or disposal elsewhere will not be returned to the Hanford Site. DOE could seek to address those concerns through technical approaches such as using a LAW treatment methodology, preceded by sampling and analysis, where waste would not be immobilized by grout unless the resulting immobilized waste would meet the waste acceptance criteria of the receiving facility. Having more than one option for out-of-state disposal would mitigate issues of access to off-site waste treatment and/or permanent disposal facilities.

[27] Grouted secondary waste would be disposed of in the IDF if such disposal is approved by Ecology. By contrast, grouted tank LAW would represent a far larger quantity than secondary waste if grouted waste were approved to be disposed of there.

[28] Treatment and disposal of tank waste offsite or out-of-state would involve some mode of transportation of the waste to the treatment or disposal facility. Transportation regulatory issues are addressed in Volume II, Appendix H.

[29] To obtain a no-migration variance, the land disposal facility would need to demonstrate that there will be no migration of hazardous constituents from the land disposal unit for as long as the waste remains hazardous. Although this is a difficult standard to meet, a number of no migration variances have been granted. In EPA (2021), EPA Region 7 proposed to reissue a "no migration" variance that the Agency had originally approved in 1990 for five underground injection well land disposal units. DOE's Waste Isolation Pilot Plant in New Mexico was also granted a conditional no migration variance by EPA; later-enacted Congressional legislation exempted the Waste Isolation Pilot Plant from the RCRA LDR requirements. The majority of no migration variances have been approved for underground injection wells (EPA530-K-05-013, *Introduction to Land Disposal Restrictions [40 CFR Part 268]*).

3.0 ANALYSIS METHODOLOGY

3.1 Current State of Technology

Vitrification and grouting are mature process technologies that have been operated at scale and that could be adapted to the specific design conditions for Hanford LAW. FBSR would effectively be a first-of-a kind facility with respect to the Hanford process configuration, waste characteristics, and scale, though its design and implementation would presumably be informed by experience with the Integrated Waste Treatment Unit facility currently being commissioned at INL that uses a different FBSR configuration.

The FFRDC team examined past and current results of experimentation regarding all three primary technologies, including both recent findings regarding immobilization fractions for iodine in glass and grout formulation, and pretreatment technology developments since the NDAA17 report (SRNL-RP-2018-00687). The team also examined pretreatment options for grouting, which include techniques for strontium-90 (^{90}Sr) removal and treatment of organic compounds. While this work is ongoing, the confidence that grout can safely be used to disposition LAW is higher now than it was at the time of the initial study. These advances and remaining uncertainties are described in more detail in Volume II, Appendix A and Appendix E, respectively.

3.2 Alternatives Development

Implementation of any of the three primary treatment technologies will require a sequence of process steps, including waste retrieval, interim storage, pretreatment to facilitate compatibility with the selected primary treatment process, air pollution control processes, disposal of the primary waste form, and treatment and disposal of solid and liquid secondary wastes. Alternatives were developed with a technical basis supporting the ability to meet necessary performance requirements as defined by federal regulatory requirements for implementation of RCRA, DOE requirements under DOE O 435.1, and NRC permitting requirements for MLLW disposal offsite, when applicable. Each treatment alternative consists of "building blocks" designed or selected to achieve each necessary process required in conjunction with the primary treatment technology to achieve a complete alternative that can comply with applicable regulations. All projects are assumed to be designed in compliance with applicable DOE Orders and requirements. The primary building blocks are:

- **Storage** of retrieved waste either in existing DSTs or new facilities
- **Pretreatment** consisting of one or more of (1) tank side cesium (and strontium) removal (TSCR), (2) ^{99}Tc removal, (3) ^{129}I removal, and (4) LDR organic chemicals destruction or removal
- **Primary treatment** consisting of either (1) vitrification, (2) FBSR, or (3) grouting
- **Primary disposal** consisting of either (1) onsite at the IDF or a new disposal unit, or (2) off-site disposal at a state or NRC-licensed MLLW facility (e.g., Energy*Solutions* [Clive, Utah] or Waste Control Specialists [Andrews, Texas])
- **Secondary waste treatment and disposal**.

Individual building blocks may be implemented at different locations (e.g., near-tank, on-site remote from the waste tanks, or offsite) and incrementally in time. Individual building blocks are summarized in Section 3.3 and further described in Volume II, Appendix C. The assumptions used as a basis for the alternatives are also included in Volume II, Appendix C.

The FFRDC team developed and evaluated 23 initial alternatives for supplemental treatment of LAW, four of which are described in Section 3.3, with all of the alternatives detailed in Volume II, Appendix C.

As specified in NDAA21, the alternatives included the three primary treatment technologies from the NDAA17 analysis (vitrification, FBSR, and grouting), with emphasis on advancing the details of the grout alternatives. A prescreening review narrowed the set of viable alternatives to 15 alternatives for detailed analysis. Subsequent assessment of the decision criteria defined in Section 4.0 showed that some alternatives employing a given primary treatment technology were "dominated" by other alternatives using the same technology. An alternative is said to be dominated if there is another alternative that scores at least as well on every decision criterion, and better on at least one (Kahneman, and Tversky, 1986). The assessment process is described in Section 4.1, and the detailed taxonomy is included in Volume I, Appendix A. The detailed analyses of the 15 alternatives are provided in Volume II, Appendix D. Some alternatives were not fully evaluated for reasons that are explained at the end of the corresponding descriptions in Volume II, Appendix C.

Once the assessments were complete, the FFRDC team selected for detailed comparison the most promising alternatives using each primary technology. With two exceptions, these were simply the undominated alternatives within that technology group.[30] These four alternatives illustrate the available performance and implementation trade-offs across and within technologies. The four selected alternatives are:

- Vitrification with on-site disposal at Hanford (Vitrification 1)
- FBSR solid monolith product with on-site disposal at Hanford (FBSR 1A)
- Grouting performed by an off-site vendor with off-site disposal (Grout 4B)
- Initial off-site grouting and disposal, followed by on-site grouting and disposal in containers (Grout 6).

Detailed implementation and LAW treatment schedules and cost bases were developed for each of the four selected alternatives (Volume II, Appendix F), assuming an annual DOE ORP benchmark budget for supplemental LAW treatment activities of $450 million in 2023 dollars. Because the NDAA21 Section 3125 did not provide budget guidance, this benchmark was selected based on comparability to the DFLAW budget.[31] The FFRDC team also assessed the robustness of its findings by performing sensitivity analysis against the precise budget level selected, future escalation rates, and the cost estimate ranges, including a completely unconstrained case. The results of this sensitivity analysis are provided in Volume II, Appendix F.

Each of the alternatives is assumed to operate in parallel with the WTP LAW Vitrification Facility, providing flexibility as to which specific tank wastes would be treated by WTP LAW vitrification or by the supplemental LAW treatment process. Out-of-state disposal was considered because the geology and expected performance of the off-site disposal facilities are different from those of the on-site disposal facility/site and offer an alternative disposal path for waste forms that may be deemed to be less suitable for on-site disposal. The FFRDC team based the analysis on the Hanford IDF and the commercial disposal sites in Clive, Utah, and Andrews, Texas.

[30] The two exceptions were alternatives Grout 1A and FBSR 1B. Grout 1A had the lowest discounted lifecycle costs among all alternatives, and was thus undominated, but scored significantly lower than other grout alternatives in both long-term performance and implementation schedule. In the judgment of the FFRDC team, the cost savings were not sufficient to make Grout 1A a highly attractive option, compared to the other undominated grout alternatives. FBSR 1B, on the other hand, was eliminated on practical grounds; while FBSR 1B scored significantly higher than FBSR 1A in estimated long-term performance, this was driven entirely by the use of off-site disposal. When off-site disposal is available, all of the off-site grouting alternatives dominate FBSR 1B in performance and risk, at much lower lifecycle cost. FBSR 1B is thus not a reasonable candidate for selection, leaving FBSR 1A as the best candidate using FBSR technology. The full set of decision criteria assessed is presented in Section 4.1.

[31] The benchmark budget was assumed available starting in 2025 and full carryover of funds was allowed. The analysis showed that all alternatives, except Vitrification 1, could be completed within the $450 million (constant fiscal year [FY] 2023 dollars) annual allowance. For Vitrification 1, a budget of $555 million would allow for construction and operations (assuming full carryover) with the operations start date of 2050. A sensitivity analysis was also conducted with the results provided in Volume II, Appendix F, Section F.2.2, with summary Table F-4.

Disposal of secondary waste was considered for each alternative. Unless the immobilization step was performed offsite, the secondary solid waste was assumed to be disposed of onsite with the exception of alternatives that considered ^{99}Tc and ^{129}I removal. In those alternatives (Grout 1C and 2C), the immobilized secondary waste containing the ^{99}Tc and ^{129}I was assumed to be disposed of offsite. Additional information is provided in Volume II, Appendix C. For each vitrification and FBSR alternative, the secondary waste could be disposed of offsite, although off-site disposal does not result in any significant change in the rankings of the alternatives for these two technologies.

3.3 Alternative Descriptions

The alternatives for supplemental treatment and immobilization of LAW are divided into three technologies: vitrification, steam reforming, and grouting. This description provides an overview of the four selected alternatives identified in this report, along with their assumptions and schematics depicting the building blocks of the simple flowsheet. The four alternatives were selected to best illustrate the three technologies and the differences among them.

All of the alternatives that were fully evaluated in this report are shown in Table 3.3-1. Vitrification and FBSR (Vitrification 1 and FBSR 1A) were assumed to result in on-site (IDF) disposal of the primary waste form. The two grout alternatives have either all off-site (Grout 4B) or a mix of off-site and on-site disposal (Grout 6) of the immobilized waste form. All alternatives include continued operation of the LAW melters in the WTP for the duration of the mission. In alternatives where waste is found to be incompatible with the immobilization method, that waste is diverted to the WTP LAW melters. More detail is provided in Volume II, Appendix C.

Table 3.3-1. Title and Description of Alternatives

Alternative designation	Alternative title	Brief description
Selected Alternatives by Technology		
Vitrification 1	Single Vitrification Plant	Construct additional melter facility; glass disposal in IDF
FBSR 1A	Fluidized Bed Steam Reforming – On-site Disposal	Construct FBSR facility; dispose monolith waste form onsite
Grout 4B	Off-site Vendor for Grouting – Off-site Disposal	Ship liquid to off-site vendor for grouting; dispose containerized grout offsite
Grout 6	Phased Off-site and On-site Grouting in Containers	Phased approach of off-site vendor grouting and off-site disposal, followed by on-site grouting and on-site disposal
Other Evaluated Alternatives		
FBSR 1B	Fluidized Bed Steam Reforming – Off-site Disposal	Construct FBSR facility; dispose granular waste form offsite
Grout 1A	Single Grout plant – On-site Disposal	Construct single grout plant in 200 East Area; dispose containerized grout in IDF
Grout 1B	Single Grout plant – Off-site Disposal	Construct single grout plant in 200 East Area; dispose containerized grout offsite
Grout 2A	Separate Grout Plants for 200 East and West Areas – On-site Disposal	Construct grout plants in 200 East and West Areas; dispose containerized grout in IDF
Grout 2B	Separate Grout Plants for 200 East and West Areas – On-site Disposal	Construct grout plants in 200 East and West Areas; dispose containerized grout offsite
Grout 4A	Off-site Vendor for Grouting – On-site Disposal	Ship liquid to off-site vendor for grouting; dispose containerized grout in IDF

Table 3.3-1. Title and Description of Alternatives

Alternative designation	Alternative title	Brief description
Grout 5A	Single Grout Plant – On-site Monolith in Vault Disposal	Construct single grout plant in 200 East Area; dispose a monolith of grout in vaults
Grout 5B	Single Grout Plant – On-site Containers in Vault Disposal	Construct single grout plant in 200 East Area; dispose containerized grout in vaults
Grout 1C	Single Grout Plant with Technetium/Iodine Removal and On-site Disposal	Remove ^{99}Tc and ^{129}I, followed by Grout 1A
Grout 2C	Separate Grout Plants for 200 East and West Areas with Technetium/Iodine Removal with On-site Disposal	Remove ^{99}Tc and ^{129}I, followed by Grout 2A
Grout 1D	Single Grout Plant with Technetium/Iodine Sample-and-Send with Off-site/On-site Disposal	Analyze LAW; grout all LAW; select on-site or off-site disposal of container based on ^{99}Tc and ^{129}I content

^{99}Tc = technetium-99.
^{129}I = iodine-129.
FBSR = fluidized bed steam reforming.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.

The alternatives were formulated based on the prior work documented in the NDAA17 report (SRNL-RP-2018-00687) and expanded to include other versions of those alternatives as conceived by team members or drawn from recently developed concepts. Only immobilization methods that are of relatively high technical maturity and had (1) been demonstrated with comparable tank waste elsewhere at laboratory scale or larger, (2) been demonstrated at large scale with radioactive streams albeit with different waste feed compositions, and (3) evidence that they could pass the basic criteria, such as meeting RCRA criteria for hazardous metals, were considered. Assessment results and comparative analysis of all 15 evaluated alternatives are summarized in Sections 4.2 and 4.3, along with additional summary analysis of the four selected alternatives. More detailed comparisons of the four alternatives are provided in Volume I, Appendix B.

To illustrate the difference in cost magnitude between vitrification and grouting options, WRPS performed TOPSim model simulations to estimate the annual costs of construction and operations for an alternative similar to Vitrification 1 and an alternative similar to Grout 4B – referred to here as "Vitrification 1 (modified)" and "Grout 4B Early Off-site Disposition". Those model runs cover the entire Hanford tank waste mission (HLW, LAW, plus LAW supplemental treatment) (Table 3.3-2).

Table 3.3-2. TOPSim Hanford Tank Waste Mission Analyses

Simulation designation	Mission analysis title	Brief description
Vitrification 1 (modified)	Single Vitrification Plant – Modified (MR-50638[a])	Construct additional melter facility – 2050 start
Grout 4B (early off-site disposition)	Off-site Vendor for Grouting – Off-site Disposal (MR-50713[b])	Ship liquid to off-site vendor for grouting; dispose containerized grout offsite

[a] MR-50638, 2021, *Analysis of Alternatives (AoA) Scenario Alternative 18 Phased Startup*, Rev. 0, Washington River Protection Solutions, LLC, Richland, Washington.
[b] MR-50713, 2022, *NDAA LAWST Modeling Study*, Rev. 0, Washington River Protection Solutions, LLC, Richland, Washington.

Pretreatment

All LAW will be pretreated to remove ^{137}Cs equivalent to or less than the WTP LAW Vitrification Facility acceptance criteria (<3.18E-5 Ci/mole Na^+ [PNNL-28958, *Cesium Ion Exchange Testing Using a Three-Column System with Crystalline Silicotitanate and Hanford Tank Waste 241-AP-107*]), which is sufficient to permit contact-handled maintenance in all subsequent processes. In all alternatives, the liquid tank waste is assumed to be processed through the Tank Farms Pretreatment (TFPT) process or a similar system(s). Pretreatment in WTP does not preclude any alternatives but may impact the final waste classification. All wastes would be sampled and analyzed or otherwise verified to be compatible with downstream pretreatment and the immobilization method prior to processing.

The TFPT, described in the System Plan (ORP-11242, Rev. 9), is similar to the TSCR system. Using TFPT primarily removes ^{137}Cs, and also removes soluble ^{90}Sr and some actinides as an added benefit of using CST.[32] Use of TFPT and its removal of ^{137}Cs, ^{90}Sr, and some actinides is included for all alternatives. Conversely, pretreatment in WTP does not remove soluble ^{90}Sr, which would result in a larger portion of the liquid waste being Class B, limiting off-site LAW disposal of that portion to only Waste Control Specialists (Texas) if disposed offsite. The modeling for the System Plan (Rev. 9, Scenario 1B) indicates 750 IX columns (i.e., TSCR-size IXC-150s) of CST would be needed to pretreat all of the LAW, and the modeling done for this report indicates ~1,000 IX columns would be needed. Neither of these model runs was optimized, so the range of 750-1,000 IX columns is assumed. Vitrification of the spent CST is the assumed disposition path. Vitrification of 1,000 IX columns of spent CST is equivalent to 2.7 wt% of CST in the HLW glass, well within the demonstrated range of 10 wt% with sludge. The CST essentially substitutes for some of the glass formers used with HLW, so no impact on the quantity of glass produced is projected. All alternative estimates include an equal cost for 1,000 IX columns and a small modular system to sluice the CST out of the IX columns.

The simplified schematic of the TFPT process is shown in Figure 3.3-1. The schematic shows a filter followed by three CST IX columns in series, although the number of columns in series may change, depending on processing needs. The unprocessed tank waste is adjusted in the DST to the target sodium ion concentration, processed through the TFPT, and the decontaminated liquid is stored in an interim storage tank prior to immobilization in the supplemental LAW treatment process. The spent CST IX columns from TFPT are interim-stored onsite, with the expectation that the media will eventually be vitrified at the WTP HLW Vitrification Facility.

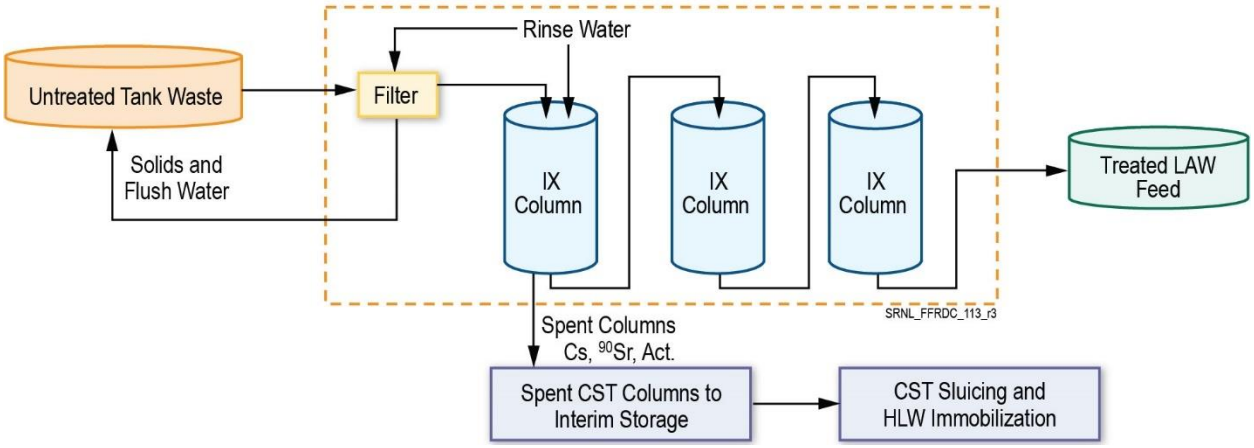


Figure 3.3-1. Tank Farms Pretreatment Process

[32] CST is used as a common descriptor of the engineered bead form of the media produced by Honeywell UOP of Des Plaines, Illinois, and is designated as Ionsiv™ 9120-B or 9140-B.

The extent of removal of soluble ^{90}Sr and actinides by CST is not known for all feed stream compositions but is estimated to be 99% and 30%, respectively, unless the waste is a complexant waste. The estimate for non-complexant waste is based on limited testing of processing Tanks AW-102, AP-107, and AP-105 through IX columns of CST (PNNL-28783, PNNL-27706, and PNNL-30712). These tanks contain blends of supernatant liquid from several tanks and are expected to be representative of the strontium chemistry in non-complexant wastes. The ability of CST to remove strontium has been known since its invention (Zheng, 1996), and its absorption is included in the computer model (ZAM) developed by its inventors. Complexant waste could contain high soluble ^{90}Sr and actinides that may or may not be removed by CST. The $SrOH^+$ ion is the species known to be removed by CST (Zheng, 1996), and this may not be a dominant form in complexant waste.

The distribution coefficient for non-complexed ^{90}Sr is approximately 10 times greater than for cesium on CST media and is expected to produce waste that is less than NRC Class A low-level limits (1 Ci/m^3). The NDAA17 report (SRNL-RP-2018-00687) indicated that 90% of waste would reach Class A if 99% of the soluble ^{90}Sr was removed. The assumed pretreatment with TSCR/TFPT IX columns to remove ^{137}Cs also results in removal of 99% of soluble ^{90}Sr from non-complexant LAW. Removing ^{90}Sr from the non-complexant LAW is not a requirement. The benefit of creating a Class A waste form is that it increases the off-site disposal options for non-complexant LAW. Only two tanks are believed to contain complexant waste, and the planned treatment involves a separate strontium/transuranic (TRU) removal process (RPP-PLAN-51288, *Development Test Plan for Sr/TRU Precipitation Process*). That Sr/TRU Precipitation Process, along with CST treatment, is likely to result in a Class B waste, limiting off-site disposal to only Waste Control Specialists (Texas), if disposed offsite.

After TFPT, the liquid will be evaporated to remove excess water; with many of the organic species in the waste expected to partition to the condensate during that evaporation (a separate evaporator is not included for vitrification[33]). Many of the LDR organic compounds suspected to be in the waste would likely be removed to concentrations below the treatment standard by the evaporation process, as documented in:

- RPP-RPT-63493, *Tank Waste LDR Organics Data Summary for Sample-and-Send*
- RPP-RPT-64064, *Distribution of LDR Organic Compounds in Hanford Tanks Waste and the Implications to LAW Treatment by Cementitious Solidification/Stabilization*
- SRNL-STI-2020-00582, *Hanford Supplemental Low Activity Waste Simulant Evaporation Testing for Removal of Organics*
- SRNL-STI-2021-00453, *Potential for Evaporation and In Situ Reaction of Organic Compounds in Hanford Supplemental LAW*
- SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*.

The aqueous condensate containing the dissolved organics from the evaporator would be sent to the ETF since it is essentially identical to the condensate from the 242-A Evaporator that is currently dispositioned in the ETF. The ETF is equipped and permitted to destroy the tank-originated organics in the 242-A Evaporator aqueous condensate stream.

[33] Evaporation for the LAW supplemental vitrification system is assumed in System Plan, Scenario 1B (ORP-11242, Rev. 9).

3.3.1 Alternative Vitrification 1, Single Supplemental Low-Activity Waste Vitrification Plant

The Vitrification 1 alternative considered in this assessment is shown in Figure 3.3-2. Disposal of the glass waste is assumed to be in the IDF in stainless steel containers. This scenario is comparable to the vitrification in the WTP LAW melter system and was included in the previous NDAA17 report (SRNL-RP-2018-00687). Because of the annual funding benchmark assumption for supplemental LAW treatment activities and the long construction time, this alternative does not begin radioactive operation until approximately 2050, which exacerbates the need for a larger facility to keep up with the HLW mission that starts in 2033. Based on information available at this time, meeting the HLW production mission schedule requires ~three times higher throughput than the current LAW melter facility to achieve the throughput needed, which corresponds to at least six LAW-sized melters. The cost for this additional melter facility increases by ~three times due to the larger facility with more melters (but cost is then discounted by 40% compared to the LAW melter facility to account for scale-up and increased design and construction efficiency).

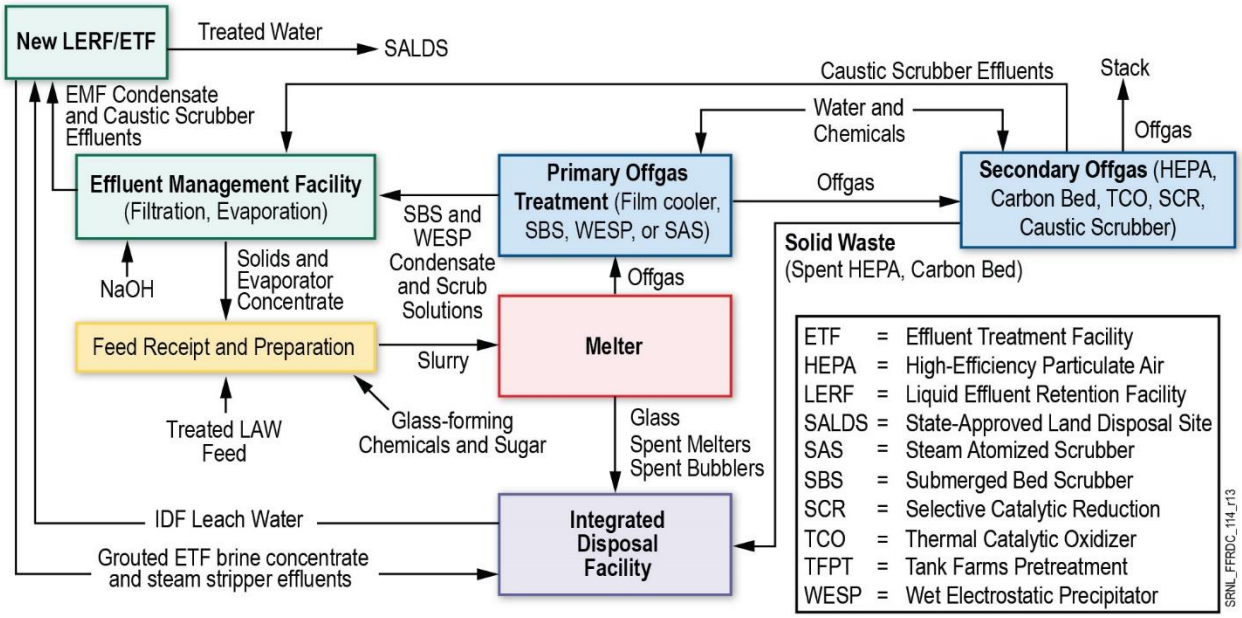


Figure 3.3-2. Flow Diagram of Vitrification

In this alternative, the existing DST system is assumed to be used to blend and stage the feed. The waste is assumed to be sampled in the DST and analyzed and found to be compliant with the pretreatment system to produce an acceptable glass waste form.

Waste vitrification technology consists of mixing a chemically characterized, aqueous waste stream with sugar, specific metal oxides, and metal carbonates to produce a slurry that is fed to a melter in which the slurry is incorporated into the melt pool. The melter is continuously bubbled by forcing air through submerged pipes in the molten pool to increase the melt rate. The volatile components are driven into offgas by heat, requiring a complex offgas system to treat the melter offgas prior to discharge and generating two secondary liquid waste streams and a solid secondary waste that also requires treatment. All water is vaporized into the offgas system, which typically has scrubbers and a condensate system that generates a liquid waste that is larger in volume than the original stream. Sulfate ion in the waste is one of the most challenging species because it has low solubility in the glass and can limit the waste loading.

The nitrates and nitrite salts are converted to ammonia, N_2, and NO_x by reaction with a reductant, such as sugar. The NO_x not captured in the primary offgas system is mostly converted to nitrogen in a catalytic reactor by reaction with added ammonia before the vapors are release to the atmosphere. A caustic scrubber further reduces the NO_x from the exhaust prior to release from the stack.

Organic chemicals present in the waste are mostly destroyed by the heat of the melter, but some others can be produced by incomplete reaction of the sugar. The mercury, ^{99}Tc, and ^{129}I are largely vaporized in the melter and collect in the offgas system. In the current WTP LAW Vitrification Facility, the offgas condensates are evaporated and recycled in an attempt to increase retention of the ^{99}Tc and ^{129}I in the glass.

Vitrification technology has been used in the U.S. and other countries to treat HLW, which is generally made up of a dilute aqueous salt solution slurry containing metal hydroxide and oxides, not a concentrated aqueous salt solution. The waste components are chemically bonded as part of the glass waste form; the interaction of the waste components with the glass-forming chemicals defines the amount of waste that can be immobilized in glass. The concentration and interaction among these components define the glass properties, such as durability. For LAW and supplemental LAW treatment, the Glass Shell v3.0 (a collection of proprietary models) is used to constrain the composition and loading of LAW glasses to control the sulfur tolerance of the melter feed to durability response, viscosity, and refractory corrosion. The final properties and composition of the vitrified waste form vary, but the models ensure that all the properties remain within acceptable processing and performance regions. The vitrified waste is poured using lifts into stainless steel containers. The containers, filled to at least 90%, are cooled, sealed, and decontaminated, and are stored temporarily prior to IDF disposal.

Glass waste loading is typically 10–25% (defined as waste sodium ion loading). The primary waste volume is reduced versus the aqueous waste, with the glass volume equivalent to ~40–50% of the liquid feed volume. The glass produced is a borosilicate glass with silica as the primary glass forming additive. Commercially produced borosilicate glass typically consists of silica, boron, aluminum, and alkali oxides, but additional glass species are present in the LAW glass as either contaminants in the waste feed (e.g., sulfur) or additives in the glass-forming chemical recipe to allow increased waste loading (e.g., tin and vanadium). Several different glass models have been developed for the expected glass waste forms to be produced during WTP LAW Vitrification Facility operations; these same models or improved versions would be expected to be used during LAW supplemental treatment operations. During processing, the composition of the feed is expected to be used to tailor a glass-forming chemical recipe that is optimized for each melter feed batch to allow the highest possible waste loading for that batch, while meeting all constraints for glass durability, conductivity, corrosion potential, density, viscosity, liquidus, and solubility limits for each species with limited solubility in glass (e.g., chromium, sulfur, selected noble metals).

When the existing LAW facility begins operations, the glass models developed in 2009 (ORP-56321, *Preliminary ILAW Formulation Algorithm Description: 24590-LAW-RPT-RT-04-0003, Rev. 1*) are expected to be used. The 2009 model has been translated into the immobilized LAW algorithm for facility use. Additional glass models have been developed that can improve the waste loading of LAW glass (PNNL-25835, *2016 Update of Hanford Glass Property Models and Constraints for Use in Estimating the Glass Mass to Be Produced at Hanford by Implementing Current Enhanced Glass Formulation Efforts*). These models are expected to be implemented once the LAW Vitrification Facility completes the commissioning process. The updated models are incorporated in the flowsheet modeling that developed the estimates for the feed to LAW supplemental treatment; therefore, the impact of the improved models is included in this analysis. The improved models have not been translated into an algorithm for use by the facility in a similar manner to the 2009 model. The feed rate, bubbling rate, and melter power are balanced in an attempt to maintain a cold cap on the melt pool. Melter offgas condensate consists of components that are volatile and semi-volatile at melter temperatures and any solids entrained into the melter offgas system. In the absence of a cold cap or during operation with a reduced cold cap, these species vaporize more completely.

All water fed to the system and the water added during primary offgas treatment processes becomes liquid secondary waste. The liquid secondary waste generated during vitrification is collected and processed through the EMF, which is expanded in this alternative to accommodate the additional volume from more melters.

This waste is collected and processed using filtration and evaporation in the EMF. The EMF evaporator bottoms are recycled to the LAW facility melter for retreatment so that the radioactive and hazardous components, such as ^{99}Tc, are forced into the glass at higher concentrations than a single-pass system would achieve.

The EMF overhead condensate and secondary offgas system liquids are transferred to the LERF/ETF for collection and further treatment. A new facility would likely be required for treatment of the supplemental LAW effluent, due to capacity limits of the current facility. Treated water from ETF is disposed of at a state-approved land disposal site (SALDS). After treatment in ETF, the concentrated brine waste from ETF is primarily an aqueous solution of ammonium and sodium sulfates. The brine concentrate stream will either be routed to the thin film dryer and made into a powder form or sent offsite to be grouted. Both waste forms will be sent to the IDF for disposal. As documented in RPP-RPT-60974, *ETF New Waste Stream Acceptance Package for WTP Effluent Management Facility*, this stream was determined to be suitable for acceptance at LERF/ETF under Revision 11 of the waste acceptance criteria (HNF-3172, *Liquid Waste Processing Facilities Waste Acceptance Criteria*). HNF-3172 has since been revised (Revision 12) due to the ETF documented safety analysis, and the WTP EMF waste stream evaluation will need to be performed again.

Solid secondary waste from the vitrification facility (e.g., high-efficiency particulate air [HEPA] filters, carbon bed media, bubblers) were assumed to be placed in a container, encapsulated in grout, and disposed of in the IDF along with the immobilized waste from the ETF. However, waste disposition will be an evolving process and efficiencies will be looked at after DFLAW operations commence.

3.3.2 Alternative FBSR 1A, Fluidized Bed Steam Reforming On-site Disposal

The FBSR process was described in the previous NDAA17 report (SRNL-RP-2018-00687). FBSR can convert radioactive liquid waste to a dry, granular mineral product. With proper controls, the mineral product consists of chemical structures that can retain the radionuclides and most other constituents of concern. FBSR has been researched, developed, and used commercially for over two decades for processing low-level radioactive wastes, but those applications are unlike the high sodium ion content, alkaline Hanford tank waste.

FBSR operates at temperatures up to 725–750°C to evaporate water in the waste, destroy organics and nitrates – converting them to carbon dioxide, nitrogen, water, and residual NO_x, and convert the solid residue into a leach-resistant waste form. Coal and oxygen are fed into the ceramic-lined vessel known as the denitration and mineralizing reformer (DMR) where they react in the presence of high temperature steam (500–600°C) to produce hydrogen and other reactive gas species.

The DMR contains a bed of particles that are the right size and density to be continually fluidized by steam that flows upward through the bed. The liquid tank waste is mixed with clay, and the slurry is sprayed into the bottom of the vessel. The remaining dissolved and undissolved components of the supplemental LAW (e.g., sodium, aluminum, halogens, sulfur, hazardous metals, and radionuclides, if present) react with the clay that is premixed with the waste feed to form the desired mineralized waste form. This product includes mineral structures of nepheline, carnegieite, sodalite, or nosean. These structures can incorporate the nonvolatile and semi-volatile elements in the waste feed either into the nepheline or carnegieite mineral structures or inside sodalite or nosean “cages” of suitable sizes to contain halogens and radionuclides. The mercury vaporizes and is captured in the offgas system. The ^{99}Tc and ^{129}I are largely but not entirely retained in the mineral waste form initially, and any that escapes is captured in the offgas system and recycled into the DMR to improve retention. No liquid waste is discharged from the FBSR system, as the system is operated such that all of the water produced in the offgas system is recycled to the DMR and eventually vaporized, treated in the offgas system, and then discharged to the atmosphere.

In the FBSR facility, two process systems operate in parallel to receive waste from a single feed system to provide the throughput and ability to vary the flow rate needed to maintain the supplemental LAW feed vector throughput. Alternative FBSR 1A (Figure 3.3-3) produces a granular product that is then converted to a monolithic primary waste form for storage and permanent disposal in the IDF on the Hanford Site.

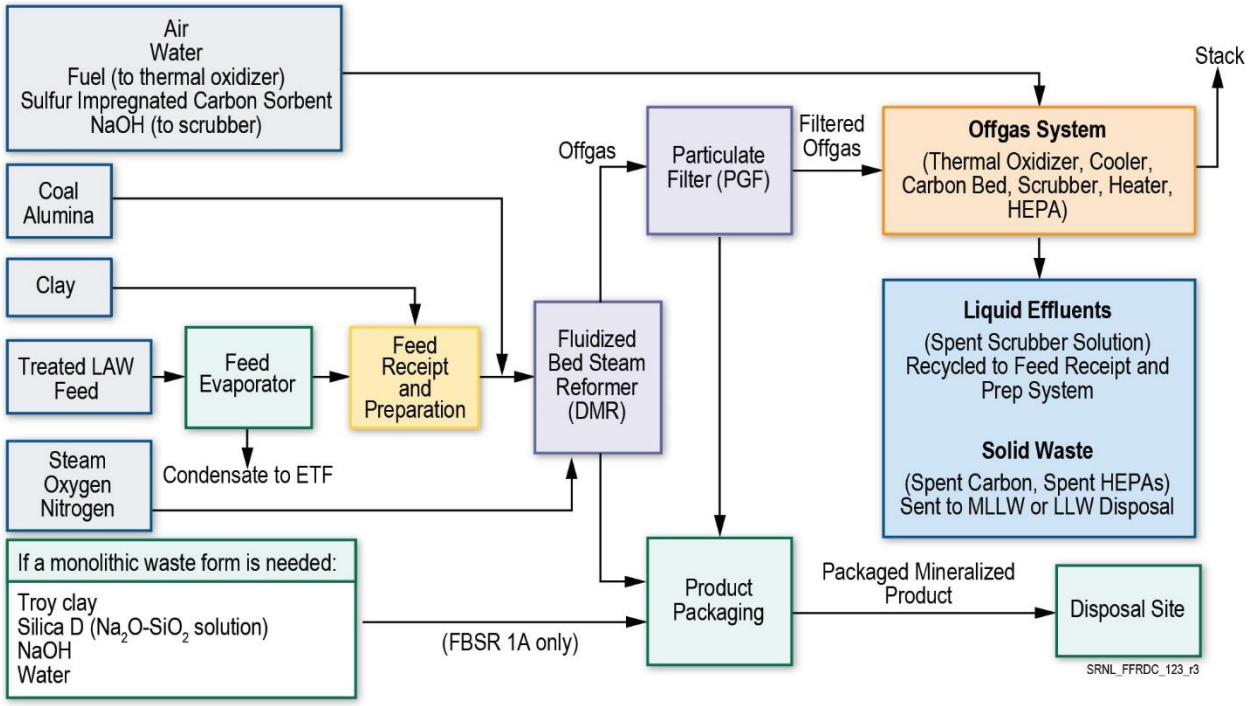


Figure 3.3-3. FBSR 1A, Fluidized Bed Steam Reforming with On-Site Disposal

A geopolymer process downstream of the FBSR converts the granular FBSR product to a monolith, which is needed to meet the 85 lb/in.^{2} (6 kg/cm^2) compressive strength limit required for IDF disposal. That step is part of the product packaging box in Figure 3.3-3, and consists of forming a grout-like waste form in containers, similar to that described below for grouting tank waste. The geopolymer process entails mixing granular FBSR product with clay, silica, caustic, and water, which is then poured into containers and cured, prior to disposal.

3.3.3 Alternative Grout 4B, Off-site Vendor for Grouting with Off-site Disposal

Extensive experience using grout waste forms has been gained in the U.S. from federal and commercial applications and as the standard immobilization technology for low-level waste (LLW) across the international community. This experience includes grouting of the supernatant portion of the tank waste at SRS[34] after treatment of the waste to remove soluble cesium, strontium, and actinides. At SRS, the grouted waste is disposed of in large on-site vaults adjacent to the Saltstone Facility. The required properties of the grout waste form in this alternative are dictated by the disposal location, the immobilization facility requirements, and chemistry of the waste. Grouting was also used to immobilize the separated LAW fraction of tank waste at the West Valley Demonstration Project, with the waste being subsequently disposed of at the Nevada Nuclear Security Site. Detailed descriptions are provided in Volume II, Appendix L.

[34] While some differences exist between the SRS and Hanford wastes, the SRS waste is the closest analog in the U.S. to the waste at the Hanford Site.

This alternative uses an off-site vendor to immobilize the treated supernatant liquid. In alternative Grout 4B, the existing DST system is assumed to be used to blend and stage the feed. Waste would first be characterized to confirm its acceptability for the off-site disposal facility to ensure that the waste produced is compatible with grouting after pretreatment and LDR organic treatment (if needed), or if not compatible, the waste would be staged for vitrification. This alternative also provides the ability to begin supplemental LAW treatment and disposal as early as 2027.

After removal of ^{137}Cs and ^{90}Sr in TFPT and LDR organic treatment, if required, the treated supernatant liquid is shipped offsite in liquid form.[35] Multiple vendors are currently available that have the technical ability to grout the waste, and one or more could be used for this service. The vendor would mix the liquid waste with grout-forming additives, ordinary portland cement (OPC), blast furnace slag (BFS), and fly ash (FA). Other additives may be used or ratios may vary, depending on composition and disposal requirements.

The grout is poured into containers, assumed to be 10 yd^3 (8.4 m^3) steel boxes that can be disassembled, each with a heavy-duty polypropylene bag liner, although other sizes, configurations, and containers may ultimately be used. Unless the disposal site is also the vendor that performs grouting, the grouted waste, compliant with respective facility waste acceptance criteria, is then sent to an off-site facility for disposal. In either case, the waste is emplaced at the disposal site (Energy*Solutions* [Clive, Utah] and/or Waste Control Specialists [Andrews, Texas]). Figure 3.3-4 shows alternatives Grout 4B, including off-site disposal.

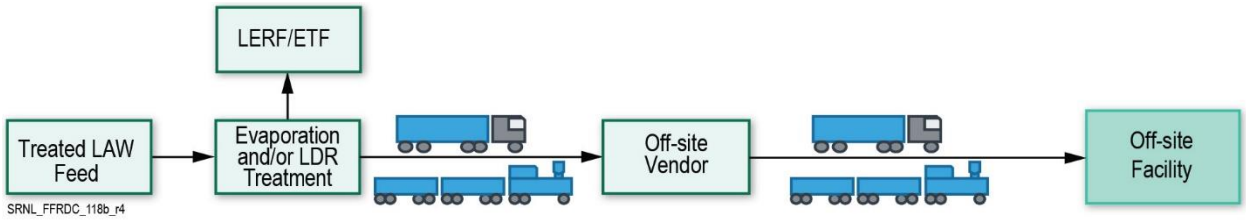


Figure 3.3-4. Flow Diagram for Alternative Grout 4B

Technical maturity for the immobilization process is high and could be performed with existing technology, assuming that the LDR organics can be removed by a separate process, if needed, for Clive disposal. This alternative could provide an early start and/or supplemental capacity for grout stabilization of the LAW.

Several factors minimize the potential for producing containers of the waste form that cannot be disposed offsite. A grouting process has a limited working inventory of liquid waste, although containers are assumed to not be shipped until some curing time has elapsed. If a problem occurs with disposal, shutting down grout production equipment is simple, limiting the material in interim status. With an extensive knowledge base of grouting comparable liquid waste, producing unacceptable grout is unlikely. Further, establishing agreements with two disposal sites in different locations minimizes the risk of producing waste with no defined disposal path.

Although not specified, the off-site vendor is assumed to have a process similar to that envisioned for the other grout alternatives evaluated in this document. That simplified typical containerized grout production flowsheet is provided in Figure 3.3-5, showing off-site disposal of the primary and secondary wastes. Secondary wastes from grouting are estimated to be small, and standard commercial practice is for the vendor to handle management and disposal.

[35] The ability to ship pretreated liquid tank waste at a small scale (3-gallon proof of concept) was demonstrated during the Hanford TBI (DOE-EM, 2018).

Grouting alternatives are based on the assumption that the waste meets regulatory requirements for LDR organics. If the liquid waste requires treatment for LDR organics, they are removed by evaporation and possibly further using methods such as low temperature oxidation. All flowsheets for grout immobilization show an on-site evaporation and LDR treatment step for consistency, although it may not be needed for some wastes. If some portion of the waste is resistant to these treatments to remove or destroy the organics, the waste is assumed to be diverted to the LAW melter for processing.[36]

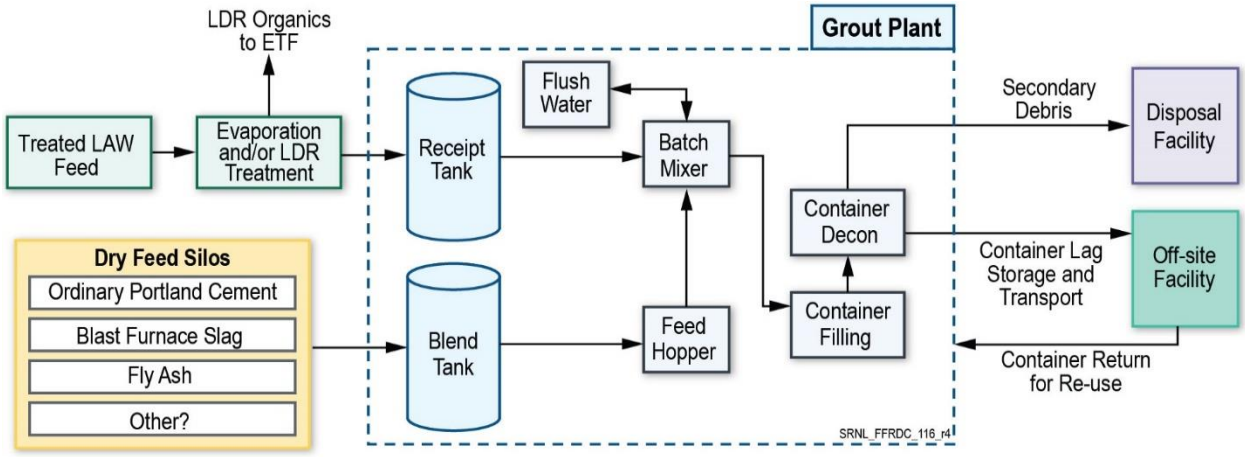


Figure 3.3-5. Typical Containerized Grout Processing Facility

Waste evaporation to both remove LDR organics and reduce waste volume are relatively mature technologies, although the effectiveness of LDR organic removal of all species is yet to be completely demonstrated. Additional treatment may be necessary to destroy some organics; any such technology has a low technical maturity level for application in Hanford tank wastes.[37] This alternative assumes that the liquid waste is sampled, analyzed, and tested as necessary prior to processing to ensure pretreatment will produce an acceptable waste form. Unlike the vitrification and FBSR alternatives, non-LDR constituents in the waste, including nitrate and nitrite ions, are not destroyed nor is NO_x vapor formed in the grouting process; these species are instead incorporated into the final waste form. Off-site disposal of a grouted waste form containing the nitrate and nitrite is anticipated to comply with the facility waste acceptance criteria and to have no impact on LDR constituents. Volume II, Appendix E, Section E.3.1.5 provides more information on nitrates/nitrites, and Volume II, Appendix A., Section A.3.6 and Appendix E, Section E.3.1.6 provides more information on LDR organics.

3.3.4 Alternative Grout 6, Phased Off-site and On-site Grouting in Containers

After evaluating the alternatives against the selection criteria, the lower construction and operating costs of all grout alternatives and the availability of off-site solidification/immobilization and disposal was found to offer the opportunity of phased implementation and early startup. This hybrid approach initially sends some pretreated low-activity liquid waste to an off-site facility for solidification/ immobilization by commercial treatment contractors and disposal at licensed off-site facilities. This approach also allows deferment of the design and construction phases of an on-site facility for the alternative. Of the alternatives with on-site immobilization, only the alternatives with on-site grout capital projects offered the financial opportunities to spend funds on these early off-site shipments. The Vitrification and FBSR alternatives required all of the assumed available benchmark funding to support the timely execution of capital projects, and any funds diverted from the projects for off-site shipments would delay the capital projects and/or increase the size of the project(s).

[36] An acceptable method to transfer the diverted waste to the WTP LAW Vitrification Facility is assumed.
[37] Low temperature oxidation was planned for treatment of organics during the initial TBI, but was not needed because the organic concentrations were below action limits.

Any additional funding expended on off-site grouting without additional funds provided would delay the startup of supplemental LAW treatment operations and further delay completion of the WTP HLW Vitrification Facility mission. Therefore, only hybrid alternatives that involve grout as the final waste form were considered.

The FFRDC team considered several potential hybrid on-site/off-site grout alternatives. The alternative with the best combination of early progress and low risk was chosen for evaluation and designated alternative Grout 6. This hybrid alternative processing begins with one process in phases and transitions to a final process of on-site grout production and disposal. This hybrid alternative gives time to develop the waste form performance information and performance assessment modeling needed to complete remaining technology maturation (e.g., characterizing waste, determining grout formulations, and maturing additives/getters) to support the final phase of on-site disposal while simultaneously making progress and working within the assumed benchmark budget for the third phase to begin.

The eventual transition to on-site production and disposal in the final phase is expected to lower the overall mission cost and therefore the overall mission duration and risk. Of course, the on-site production and disposal alternative could instead be initiated immediately, avoiding off-site production and disposal. However, this approach is not the fastest at reducing risk of tank leaks, in part because it is reliant on the timing for approvals and the federal budget cycle, followed by grout plant construction time. If the off-site production and disposal is deemed infeasible due to unforeseen issues, the early construction and startup of the most favorable on-site alternative would be able to gain at least some advantage of the early removal of liquid waste from the tanks.

Another consideration is that there could be opportunities for co-locating a modular grout-production system, along with planned waste retrieval infrastructure in some tank farms; this approach was not fully evaluated as it is not envisioned to be the most cost-effective or fastest way to complete the entire LAW supplemental treatment mission, which is the objective of this evaluation. Using multiple modular systems was not fully evaluated for reasons described in Volume II, Section C.12, largely because of the need for constructing supporting infrastructure at multiple locations.

Alternative Grout 6 is a phased approach that combines aspects of alternatives Grout 4B (off-site vendor, off-site disposal) beginning in 2027 and aspects of Grout 2B (separate pretreatment plants with off-site grouting and disposal) in phased startup in 2034–2035, and transitions to on-site grouting in the 200 East Area with the on-site disposal approach beginning in 2040 (Volume II, Appendix C provides details on each alternative). Similar to alternative Grout 4B, waste would first be characterized to confirm its acceptability for the disposal facility to ensure that the waste produced has a defined disposal path. After removal of ^{137}Cs and ^{90}Sr in TFPT and LDR organic treatment, if required, the treated supernatant liquid is shipped offsite in liquid form. Since the off-site contractor is handling immobilization and disposal is offsite in this phase, the contractor would choose both the immobilization technique and the final packaging size and type. For this study, standard grout is assumed for costing purposes. Construction of the TFPT, LDR treatment, and a load-out station onsite would be needed, along with permitting for processing and disposal. The schematic for this phase is the same as that shown in Figure 3.3-4.

Multiple vendors are currently available that have the technical ability to grout the waste and one or more could be used for this service; additional permitted providers could also become available in the future. The schematic for the subsequent phase, comparable to pretreatment aspects of Grout 2B, is shown in Figure 3.3-6. A 200 East Area plant could instead perform grout production in this phase, along with off-site disposal in 2035–2039 (i.e., alternative Grout 2B), although this was not the assumed configuration in the cost profile.

The choice of on-site disposal scenario in Phase 3 (in containers in IDF similar to alternative Grout 1A or in a monolith/containers in a vault similar to alternatives Grout 5A or 5B) will be decided as a result of technology maturation and permitting activities before 2040. The alternative Grout 5B approach was assumed for costing in this phase, since this alternative is expected to be the most expensive of these three alternatives; however, the Grout 1A approach was used for the technical evaluation because the alternative is expected to have the lowest technical certainty, in part due to the need for getter development. Ultimately, if on-site grout disposal is found not viable, the backup option would be to dispose of all grouted waste offsite (i.e., continue as in alternative Grout 4B).

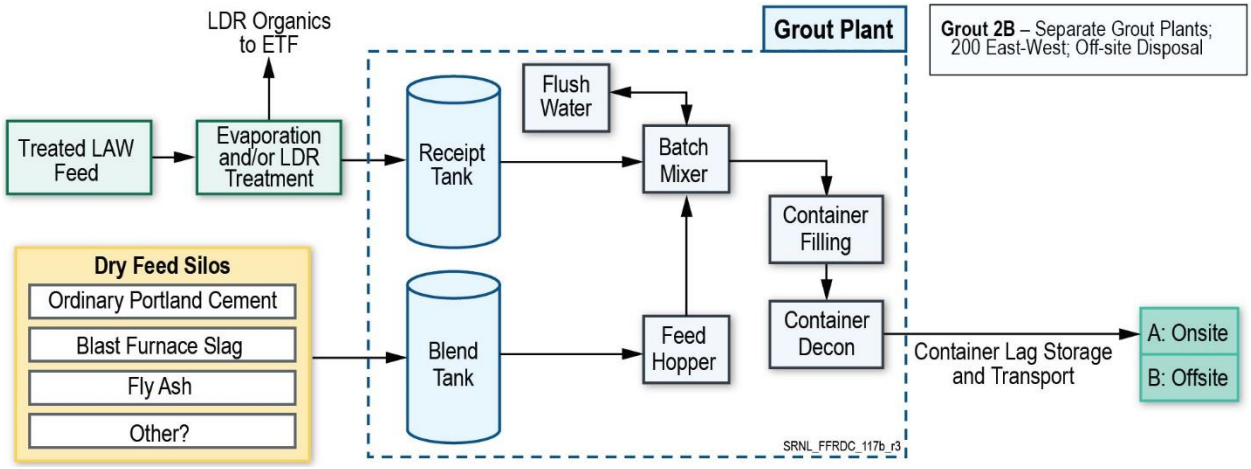


Figure 3.3-6. Schematic of Containerized Grout Production Onsite, with Off-site or On-site Disposal

The purpose of this alternative is to expedite retrieval and disposal of wastes. The hybrid concept of this alternative is to initially pretreat the waste in the 200 West Area, and a second phase consisting of the TFPT and LDR treatment process system would be constructed and operated in the 200 East Area. A second TFPT and LDR treatment process system would be constructed and operated in the 200 East Area, with the same off-site grouting and disposal steps, similar to alternative Grout 4B. Because much of the ^{99}Tc and ^{129}I is soluble and is at the highest concentration in the waste projected to be treated in the early phases, a disproportionate share (e.g., 10,000 Ci ^{99}Tc offsite versus 7000 Ci ^{99}Tc onsite) of the radionuclide inventory (as opposed to volume of waste) will be disposed of offsite. This "risk reduction" in alternatives Grout 4B and Grout 6 is discussed further in Section 3.4.

This alternative assumes off-site supplemental LAW treatment operations through the final years of DFLAW operations and in support of the WTP HLW Vitrification Facility startup. During the start-up and initial operations of the WTP HLW Vitrification Facility, the on-site grouting capacity will be developed and constructed in the 200 East Area. On-site grouting operations will commence in 2040 and run in parallel with off-site grouting until full capacity is realized. At this point, the WTP LAW Vitrification Facility and on-site grouting will suffice for balance of mission LAW feed immobilization. Although not included in this evaluation, if needed depending on the pace of the 200 West Area saltcake-rich SST retrievals, an additional grouting plant could be constructed near the SY Farm.

The evaluation of this alternative assumes that the iodine (^{129}I) getter is included in the grout formulation for the final phase, with on-site container disposal in IDF. However, the work in the interim period may identify that technetium and iodine removal or disposing the waste form as containers in vault (without getters) for on-site disposal is optimal (the vault approach was used for estimating). Unlike the vitrification and FBSR alternatives, non-LDR constituents in the waste, including nitrate and nitrite ions, are not destroyed nor is NO_x vapor formed in the grouting process; these species are instead incorporated into the final waste form.

Off-site disposal of a grouted waste form containing the nitrate and nitrite is anticipated to comply with the facility waste acceptance criteria and have no impact on LDR constituents. On-site disposal of the grouted waste form in Phase 3 is anticipated to be compliant with groundwater standards, but a performance assessment considering multiple variables, including the inventory to be disposed of onsite, would be required prior to disposal to assess groundwater impacts during the compliance and post-compliance periods.

Early start of LAW processing, particularly in the 200 East Area, alleviates DST space limitations and allows for the WTP HLW Vitrification Facility mission support as required for caustic dissolution of aluminum and sludge washing. These support operations will likewise generate LAW feed; the additional feed will be processed in conjunction with existing and SST retrieved supernatant liquids.

3.4 Risk Reduction and Mission Cost Profile as a Function of Low-Activity Waste Supplemental Treatment

Supplemental LAW treatment is needed to increase the work-off rate of the tank waste volume to support the overall retrieval/storage/preparation system capacity to allow HLW vitrification to effectively pace the RPP clean-up mission. This function is the reason supplemental LAW treatment was first proposed. The start-up and operations of supplemental treatment have a significant impact on the overall mission, as demonstrated by the previously discussed TOPSim results. The risk reduction (gallons and curies removed) and relationship to incurred cost versus time for the four selected alternatives is shown in Table 3.4-1.[38,39] There is a significant difference among alternatives regarding potential technetium disposition. This is due to the concentration of technetium in the initial LAW feed.

The initial LAW feed is currently the supernatant liquid in the DSTs and is significantly enriched in soluble technetium versus the precipitated salt in the SSTs.[40] In effect, while the volumetric reduction capabilities of LAW supplemental treatment are closely tied to the overall mission duration, the disposition of technetium is more closely connected to the initiation of LAW feed consumption. For reference, the WTP LAW Vitrification Facility will process nominally 10,000 Ci of technetium in the first 27 years of operations (2023–2050) during the Vitrification 1 (modified) TOPSim model run scenario, but just under 2,000 Ci of technetium in the final 25 years (2050–2075). Analogously, if DFLAW operations are delayed past 2023, proportionately greater technetium/iodine would be processed via early off-site disposition options and removed permanently from the Hanford Site.

[38] The TSCR unit constructed to support the DFLAW program started to generate feed in January 2022.

[39] Key mission activity dates reflect the last year prior to facility start. For reference, the current target date for HLW vitrification start is December 31, 2033. For vitrification, the assumed 2048 start of operations is consistent with the earliest projected start, allowing for 2 years additional operations and maximum technetium incorporation for that alternative (Vitrification 1).

[40] Technetium is distributed in the various quadrants based on the plutonium separations facility location and mission timing. Technetium in the northwest and northeast quadrants is derived from T and B Plant operations, respectively. These plants operated from the Manhattan project era and effectively split the incoming fuel (technetium source) through 1956. A small amount of technetium was processed through the REDOX plant located in the southwest quadrant. From 1956 on, the majority of fuel was processed at the PUREX plant, with fission products distributed throughout the southeast quadrant.

Table 3.4-1. Comparison of Cost and Projected Performance of Four Selected Low-Activity Waste Supplemental Treatment Alternatives

LAW Supplemental Treatment Alternative	Cumulative unescalated cost | Constant FY 2023 value ($M, rounded)				Cumulative supplemental LAW feed treated Mgal | Ci (Tc)			
	2033[a]	2039[b]	2047[c]	At Treatment Alternative Mission End[d]	2033[a]	2039[b]	2047[c]	At Treatment Alternative Mission End[d] (% Tc treated)
Vitrification 1	2,200 | 4,100	5,600 | 6,800	8,100 | 10,400	23,400 | 27,000 [2075[d]]	-	-	-	83[e] | 6,640 (27%)
FBSR 1A	1,600 | 2,100	3,500 | 4,600	4,800 | 5,900	8,400 | 9,900 [2070[d]]	-	-	25 | 5,700[e]	86[e] | 10,210 (41%)
Grout 4B	1,300 | 1,300	2,500 | 2,600	4,000 | 4,100	6,400 | 6,900 [2066[d]]	14 | 6,900	34 | 10,100	58 | 12,600	97 | 17,000 (68%)
Grout 6	1,400 | 1,600	3,200 | 3,600	4,100 | 4,800	5,800 | 6,900 [2066[d]]	14 | 6,900	34 | 10,100	58 | 12,600	97 | 17,000 (68%)

[a] Key mission activity: 2033 – Start of HLW vitrification (assumed end of year).
[b] Key mission activity: 2039 – Start of FBSR for supplemental LAW treatment (assumed end of year).
[c] Key mission activity: 2047 – Start of vitrification for supplemental LAW treatment (assumed end of year).
[d] The mission end date varies by treatment technology.
[e] For alternative Grout 4B, the technetium curies dispositioned are taken directly from the TOPSim model run. Alternative Grout 6 (with same 2026 start date) is assumed to have the same feed vector – understanding that technetium treated from 2040 on (6,000 Ci) would be dispositioned onsite in IDF versus offsite. For alternative Vitrification 1, the technetium curies treated are adjusted from the Vitrification 1 (modified) TOPSim model run by adding 3× the nominal technetium curies treated by LAW vitrification over that same period. Technetium treated by dates for alternatives FBSR 1A and Grout 1A were similarly projected based on nominal LAW vitrification technetium performance – assuming the alternatives would see the same feed vector as LAW vitrification. Projected volumes for process alternatives were calculated in a similar manner using the annual feed volumes projected for the process alternatives in this study and bounded by the TOPSim modeling results.
[f] Grout 1A is included in this chart to reflect the performance with respect to gallons of supplemental LAW treated and curies treated. Grout 1A is consistent with all Grout 1, 2, 3, and 5 process feed vectors.

Ci = curie. HLW = high-level waste. MCi = million curies.
FBSR = fluidized bed steam reforming. IDF = Integrated Disposal Facility. Mgal = million gallons.
FY = fiscal year. LAW = low-activity waste. Tc = technetium.

This concept is important as it demonstrates a diminishing return on technetium disposition versus volume processed. As the mission progresses from feed currently stored as supernatant liquid to feed derived from SST retrievals, there is noticeable reduction in technetium concentration. The supplemental LAW treatment technologies will all process between 80 and 100 Mgal (300 to 380 million L) of LAW feed. Alternatives with deferred starting dates will ultimately disposition fewer technetium curies via supplemental treatment, and force longer, higher cost missions. From that basis, alternative Vitrification 1, with the highest cost by a nominal factor of three and a disposition of one-third of the technetium curies, provides the lowest return on investment.

4.0 COMPARATIVE ANALYSIS

Section 3125 of NDAA21 lists specific factors to be considered in the FFRDC analysis, including some carried forward from Section 3134 of NDAA17. To the extent possible, GAO Best Practices and DOE G 413.3-22, *Analysis of Alternatives Guide*, were used during criteria development and performance of the comparison of alternatives. Existing frameworks were sought for decision-making that would be useful in the development of a taxonomy of criteria with maximum relevance to decision-makers when selecting an alternative to pursue. DOE and EPA frameworks (e.g., DOE G 413.3-22, EPA RCRA and CERCLA remedy selection methodologies) were used to provide a well-established basis in the development of criteria. These criteria were tailored to best apply in the context of supplemental treatment of LAW.

4.1 Decision Forming Criteria

The high-level criteria used in the comparative analysis were:

1. Long-term effectiveness (environmental and safety risk after disposal)
2. Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)
3. Likelihood of successful mission completion (including technical, engineering, and resource-related risks)
4. Lifecycle costs (discounted present value)

Long-term effectiveness (environmental and safety risk after disposal) assesses the long-term performance of the proposed waste form in its final disposal site. Assessment of this criterion for a given alternative addresses the estimated ability of the alternative to destroy or neutralize toxins, to immobilize toxins and radionuclides away from all potable water and natural environments, and any long-term greenhouse gas emissions from the final waste form(s) after disposal. This assessment also considers the degree of confidence in the performance estimates, based on past and ongoing research into waste form performance. All alternatives considered are expected to meet current applicable disposal requirements under RCRA, AEA, state, and NRC permitting requirements.

Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration) assesses the risks to human safety and the environment during design, construction, commissioning, and operations of each treatment alternative. While the FFRDC team considered all physical, chemical, and radiological risks (and greenhouse gas emissions), those risks associated with the ongoing degradation of aging waste storage tanks at Hanford, the overall duration of activities to empty the waste tanks, and processing flexibility during operations had the strongest influence on the overall assessments.

Likelihood of successful mission completion (including technical, engineering, and resource-related risks) recognizes that the benefits of any alternative are only realized if the alternative can be executed to accomplish removal and disposition of all primary and secondary wastes. This criterion aligns closely with the "Implementability" criterion used in the RCRA and CERCLA guidance for development and screening of remedial actions. In addition to assessing technical and engineering risks to project and mission completion, the FFRDC team also assessed risks due to required resources, including peak annual funds and average annual construction costs. A benchmark budget of $450 million/year (fiscal year [FY] 2023 dollars, solely for supplemental LAW treatment activities) was used to estimate schedules and the impact of peak funding requirements on the likelihood of successful completion. Sensitivity to the level of the benchmark budget was assessed, confirming that the differences in qualitative scores for Criteria 2 and 3 among the alternatives are robust over a wide range of possible average annual budgets. Details of these sensitivity analyses are provided in Volume II, Appendix F.

Lifecycle costs (discounted present value) estimate the total commitment of public funds needed to implement each alternative. The construction estimates developed for this study were constrained to fit within a benchmark average annual funding level, and therefore are not directly comparable to past unconstrained estimates unless noted.[41] The budget constraint results in considerable construction schedule expansion for some of the alternatives, relative to their unconstrained project estimates. That schedule expansion in turn leads to additional costs, in addition to adding to duration-sensitive risks. The cost estimates developed for this analysis underestimate the cost impact of schedule delays, in that they do not account for inefficiencies in project execution resulting from reduced pace of implementation. Operations schedules, which are driven by the outputs of the WTP HLW Vitrification Facility processing, were not constrained in annual funding, nor were they allowed to stretch. Instead, any differences between the benchmark budget and the funds required to process LAW in particular years were calculated and accumulated. Discounted total excesses/shortfalls under the flat budget are reported for each alternative. Discounting, escalation assumptions, and sensitivity analyses (with unconstrained funding) are explained in Volume II, Appendix F.

For these four top-tier primary decision-informing criteria, a hierarchical taxonomy of relevant lower-tier criteria was developed to support systematic and structured analysis. Findings of prior research (including quantitative metrics where available) were incorporated into this taxonomy. The detailed lower-tier criteria were matched against the NDAA21 criteria to ensure that all were addressed in the analysis. The details of this comparative analysis are presented in Volume II, Appendix D. Assessment of the full taxonomy of criteria also provided the team with a detailed understanding of each alternative, including differences and similarities. Following the analysis of each alternative against lower-tier criteria using applicable measures of effectiveness, higher-tier criteria were iteratively evaluated based on the lower-tier findings and the team's expert judgment of the relative contributions of the criteria to risk and effectiveness. Once all tiers of the taxonomy had been evaluated for each alternative, the alternatives were analyzed comparatively based on the resulting assessments of the four top-tier criteria. A complete traceback of how the top-tier assessments derive from the lower tiers is provided in Volume II, Appendix D. A crosswalk showing how this taxonomy of criteria incorporates all of the factors and sources of evidence specified in the text of Section 3125 of NDAA21 is provided in Volume I, Appendix E.

Two other decision criteria relevant to decision-makers were identified by the FFRDC team, but were deliberately excluded from the direct comparison and ranking of alternatives, as discussed in Section 4.3.

5. Securing and maintaining necessary permits/authorities (regulatory approval)
6. Community/public acceptance (state/local)

During the assessment process, the FFRDC team adjusted the taxonomy as additional relevant factors and criteria were identified. In the end, only four to five distinct qualitative levels were assigned for each of Criteria 1 to 3, across the 15 specific alternatives considered. The team crafted text descriptions for interpretation of those levels and ranked them in order of desirability within each criterion.

[41] Unconstrained estimates for the four selected alternatives are provided in Volume II, Appendix F.

4.2 Assessment Results

The results of the assessment process, and the specific alternatives scored at each level, are shown below.

- **Criterion 1**: Long-term effectiveness (environmental and safety risk after disposal) – also referred to in Figure 4.3-1, Figure 4.3-6, Figure 4.3-7, and Figure 4.3-8 as "performance" for brevity
  - Highly effective, low uncertainty (Grout 1B, 2B, 4B, FBSR 1B)
  - Effective, low uncertainty (Grout 1D)
  - Highly effective, moderate uncertainty (Grout 6)
  - Effective, moderate uncertainty (Grout 1C, 2C, 5A, 5B, FBSR 1A)
  - Moderately effective, moderate uncertainty (Grout 1A, 2A, 4A, Vitrification 1)
  - For Vitrification 1, further clarification was made that the vitrified waste form was assessed as highly effective, but the disposition of secondary wastes was only moderately effective.
- **Criterion 2**: Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration) – also referred to in Figure 4.3-1, Figure 4.3-6, Figure 4.3-7, and Figure 4.3-8 as "promptness"
  - 2027 operations, 2065 completion, low risk with flexibility (Grout 6)
  - 2027 operations, 2065 completion, moderate risk (Grout 4A, 4B)
  - 2036 operations, 2068 completion, low risk (Grout 1A, 1B, 1C, 1D, 2A, 2B, 2C, 5A, 5B)
  - 2040 operations, 2070 completion, high risk (technical) (FBSR 1A, FBSR 1B)
  - 2050 operations, 2075 completion, high risk (schedule) (Vitrification 1).
- **Criterion 3**: Likelihood of successful mission completion (including technical, engineering, and resource-related risks) – also referred to in Figure 4.3-1, Figure 4.3-6, Figure 4.3-7, and Figure 4.3-8 as "feasibility"
  - Considerable funding margin, very high probability of completion, low uncertainty (Grout 1A, 1B, 1D, 4A, 4B)
  - Moderate funding margin, high probability of completion, low uncertainty (Grout 1C, 2A, 2B, 2C, 5A, 5B, 6)
  - Low funding margin, low probability of completion, low uncertainty (FBSR 1A, FBSR 1B)
  - Significant funding shortfall, extremely low probability of completion, low uncertainty (Vitrification 1).
- **Criterion 4**: Lifecycle costs (discounted present value) – Discounted lifecycle costs comprise the costs required prior to the beginning of operations and the costs required for operations. This information is shown in Table 4.2-1 with ranking of alternatives from best (lowest cost) to worst (highest cost) based on the total discounted present value lifecycle costs.

Table 4.2-1. Lifecycle Costs, Lowest to Highest (discounted present values, $M)

Alternative	Pre-Operations	Operations	Total
Grout 1A	1,108	1,622	2,730
Grout 1C, 1D	1,200	1,915	3,115
Grout 4A	411	2,927	3,338
Grout 5A, 5B	1,735	1,614	3,349
Grout 2A	1,544	1,851	3,395
Grout 1B	1,108	2,306	3,414
Grout 2C	1,636	2,211	3,847
Grout 4B	410	3,444	3,854
Grout 6	1,393	2,734	4,127
Grout 2B	1,544	2,774	4,318
FBSR 1A	3,375	2,152	5,527
FBSR 2A	3,374	2,905	6,279
Vitrification 1	7,608	5,092	12,700

FBSR = fluidized bed steam reforming.

4.3 Comparative Analysis

Figure 4.3-1 through Figure 4.3-3 show the FFRDC team's assessments of the qualitative decision criteria (Criteria 1–3) in pairwise comparisons highlighting the tradeoffs in performance against the criteria for the alternatives.

Criterion 1 – Long-Term Effectiveness (Better ↑)	2050 Operations, 2075 Completion, High Risk (Schedule)	2040 Operations, 2070 Completion, High Risk (Technical)	2036 Operations, 2068 Completion, Low Risk	2027 Operations, 2065 Completion, Moderate Risk	2027 Operations, 2065 Completion, Low Risk with Flexibility
Highly Effective, Low Uncertainty		FBSR 1B	Grout 1B Grout 2B	Grout 4B	
Effective, Low Uncertainty			Grout 1D		
Highly Effective, Moderate Uncertainty					Grout 6
Effective, Moderate Uncertainty		FBSR 1A	Grout 1C Grout 2C Grout 5A Grout 5B		
Moderately Effective, Moderate Uncertainty	Vitrification 1		Grout 1A Grout 2A	Grout 4A	

Better → Criterion 2 – Implementation Schedule and Risk

Figure 4.3-1. Pairwise Comparison, Performance and Promptness

Criterion 1 – Long-Term Effectiveness (Better ↑)	Significant funding shortfall, extremely low probability of completion, low uncertainty	Low funding margin, low probability of completion, low uncertainty	Moderate funding margin, high probability of completion, low uncertainty	Considerable funding margin, very high probability of completion, low uncertainty
Highly Effective, Low Uncertainty		FBSR 1B	Grout 2B	Grout 1B Grout 4B
Effective, Low Uncertainty				Grout 1D
Highly Effective, Moderate Uncertainty			Grout 6	
Effective, Moderate Uncertainty		FBSR 1A	Grout 1C Grout 2C Grout 5A Grout 5B	
Moderately Effective, Moderate Uncertainty	Vitrification 1		Grout 2A	Grout 1A Grout 4A

Better → Criterion 3 – Likelihood of Successful Project Completion

Figure 4.3-2. Pairwise Comparison, Performance and Feasibility

Criterion 2 – Implementation Schedule and Risk	Significant funding shortfall, extremely low probability of completion, low uncertainty	Low funding margin, low probability of completion, low uncertainty	Moderate funding margin, high probability of completion, low uncertainty	Considerable funding margin, very high probability of completion, low uncertainty
2027 Operations, 2065 Completion, Low Risk with Flexibility			Grout 6	
2027 Operations, 2065 Completion, Moderate Risk				Grout 4A Grout 4B
2036 Operations, 2068 Completion, Low Risk			Grout 1C Grout 2A Grout 2B Grout 2C Grout 5A Grout 5B	Grout 1A Grout 1B Grout 1D
2040 Operations, 2070 Completion, High Risk (Technical)		FBSR 1A FBSR 1B		
2050 Operations, 2075 Completion, High Risk (Schedule)	Vitrification 1			

Better

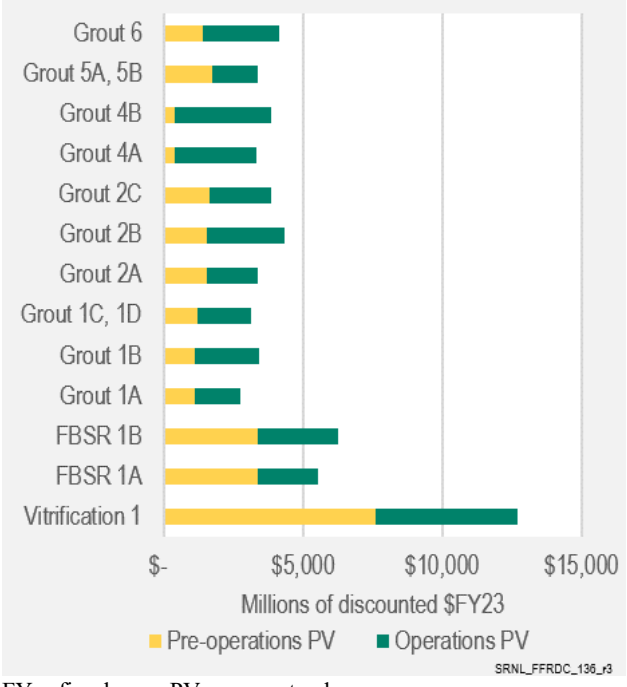
Better

Criterion 3 – Likelihood of Successful Project Completion

Figure 4.3-3. Pairwise Comparison, Promptness and Feasibility

Figure 4.3-4 shows the total discounted cost (present value) for each of the 15 alternatives. (Volume II, Appendix F, Section F.2.2 provides definitions of present value and discounting terminology.)

To permit visual comparison of the alternatives, the FFRDC team calculated rank values for each alternative against each criterion. These scores denote the number of alternatives that scored worse on that criterion, among the 15. Higher values thus indicate better performance. The figures do not indicate relative scores of the criteria. The bars in the figures reflect the number of alternatives that scored worse than a particular alternative for that criterion. This convention means that some alternatives are not shown in a figure because they did not score better than any alternative for that particular criterion.



FY = fiscal year, PV = present value.

Figure 4.3-4. Lifecycle Costs of Alternatives

Figure 4.3-5 shows these rank values graphically. This method of comparison generally understates the magnitude of the qualitative differences in the assessments for Criteria 1–3. The details of the underlying assessments for the qualitative criteria (Criteria 1–3) are provided in Volume II, Appendix D.

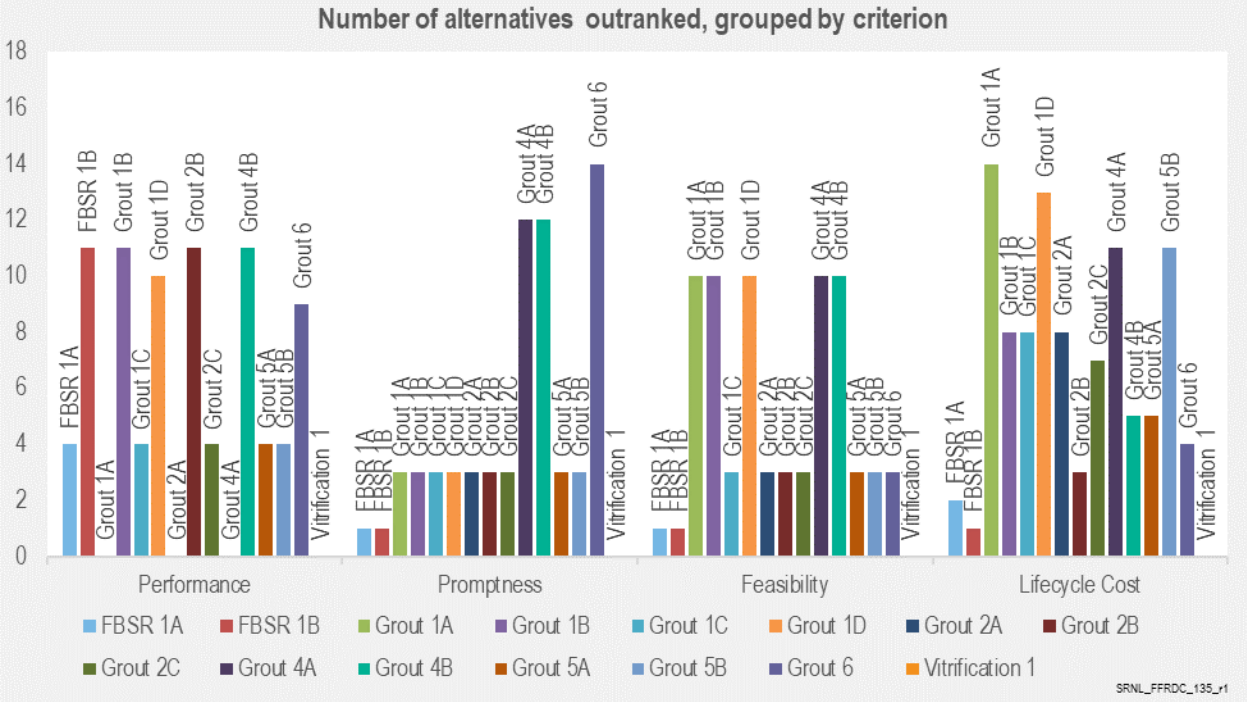


Figure 4.3-5. Number of Alternatives Outranked, by Criterion

As described in Section 3.3, the FFRDC team selected four alternatives that were considered the best representatives of the treatment technologies: FBSR 1A, Grout 4B, Grout 6, and Vitrification 1. Figure 4.3-6 shows the rank value comparison for only these four alternatives, grouped by criterion. Figure 4.3-7 shows the same comparison, grouped by alternative. Because Vitrification 1 does not outrank any other alternatives, its representative bars do not appear in these figures.

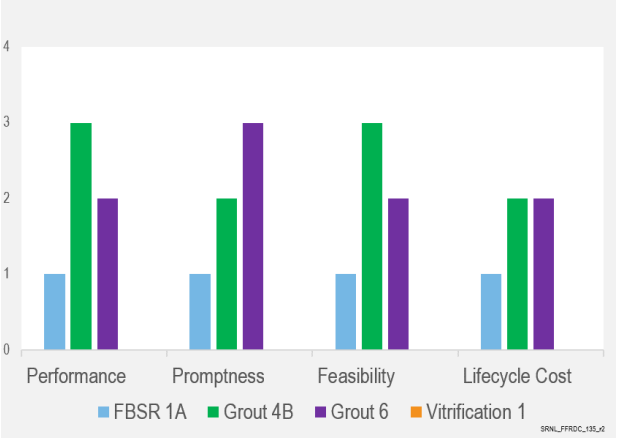


Figure 4.3-6. Number of Alternatives Outranked, Four Selected Alternatives, Grouped by Criterion

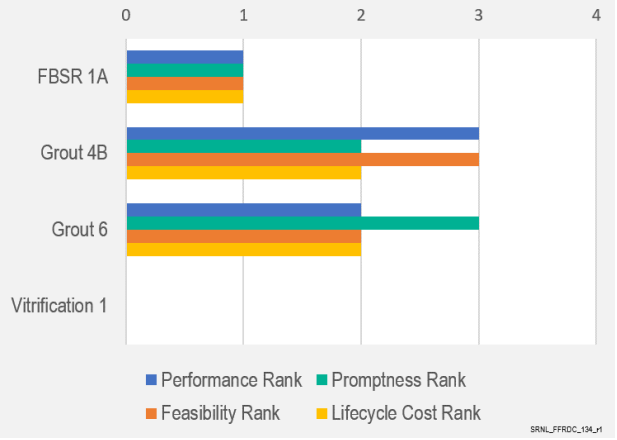
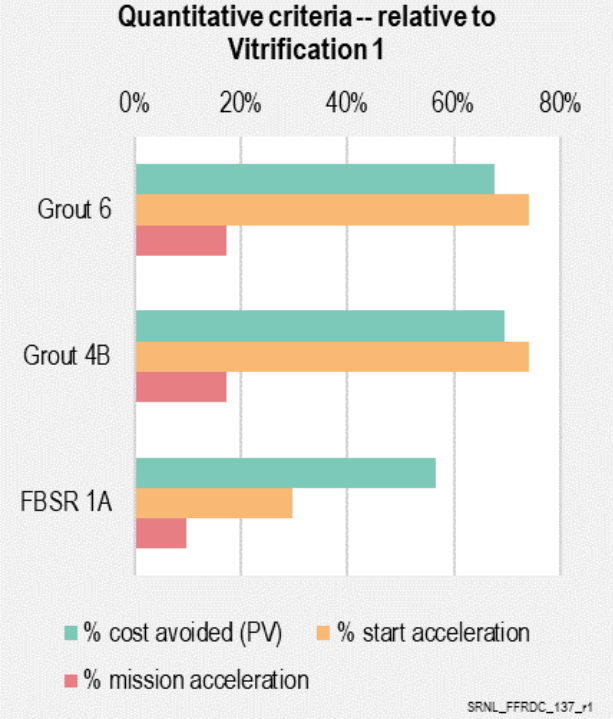


Figure 4.3-7. Number of Alternatives Outranked, Four Selected Alternatives, Grouped by Alternative

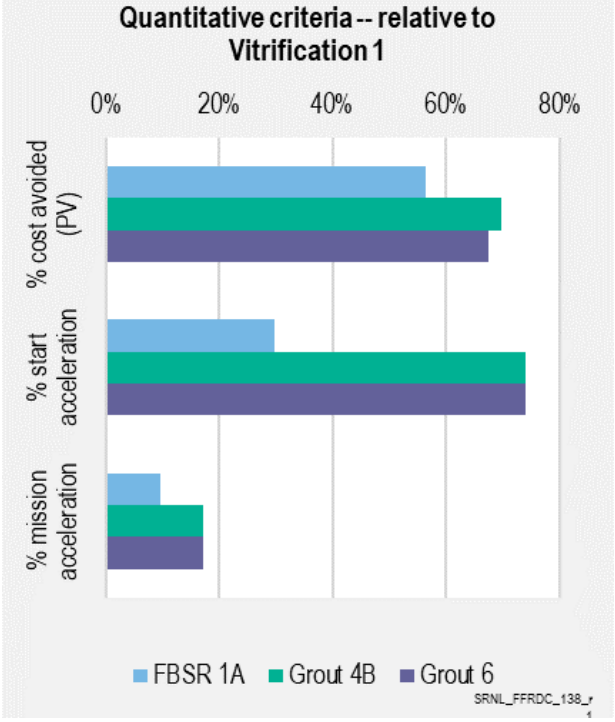
Figure 4.3-8 compares the cost and schedule reduction relative to alternative Vitrification 1 for the four selected alternatives. Figure 4.3-9 shows the same comparison, grouped by criterion.



Start acceleration = the number of years before treatment of supplemental treatment of LAW can begin.

Mission acceleration = the number of years before the last supplemental waste is treated.

Figure 4.3-8. Cost and Schedule Reduction Relative to Alternative Vitrification 1



Start acceleration = the number of years before treatment of supplemental treatment of LAW can begin.

Mission acceleration = the number of years before the last supplemental waste is treated.

Figure 4.3-9. Cost and Schedule Reduction Relative to Vitrification, Grouped by Criterion

To depict relative cost and schedule desirability of alternatives, the FFRDC team noted that the Vitrification 1 alternative had the greatest cost, the longest delay to beginning supplemental treatment of LAW, and the latest completion of the treatment mission. Cost and schedule assessments were therefore measured as the costs or duration avoided relative to the Vitrification 1 alternative.

Figure 4.3-10 shows the tradeoffs between cost avoidance and time to begin supplemental treatment of LAW among the 15 alternatives.

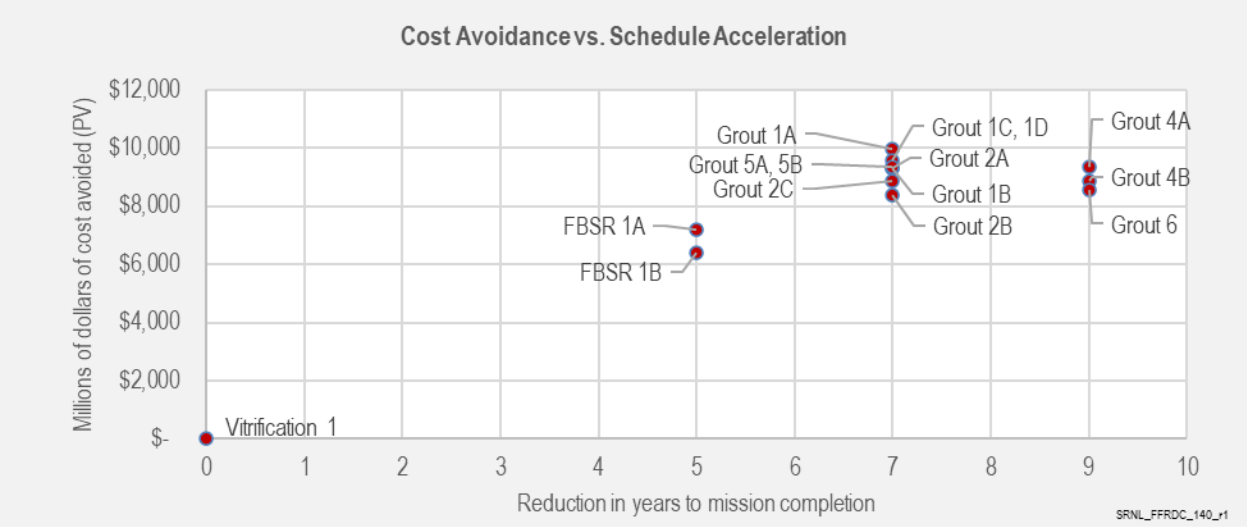


Figure 4.3-10. Cost Avoidance vs. Schedule Acceleration, Overall Mission

Figure 4.3-11 shows the analogous tradeoffs between cost avoidance and time to complete the RPP mission.

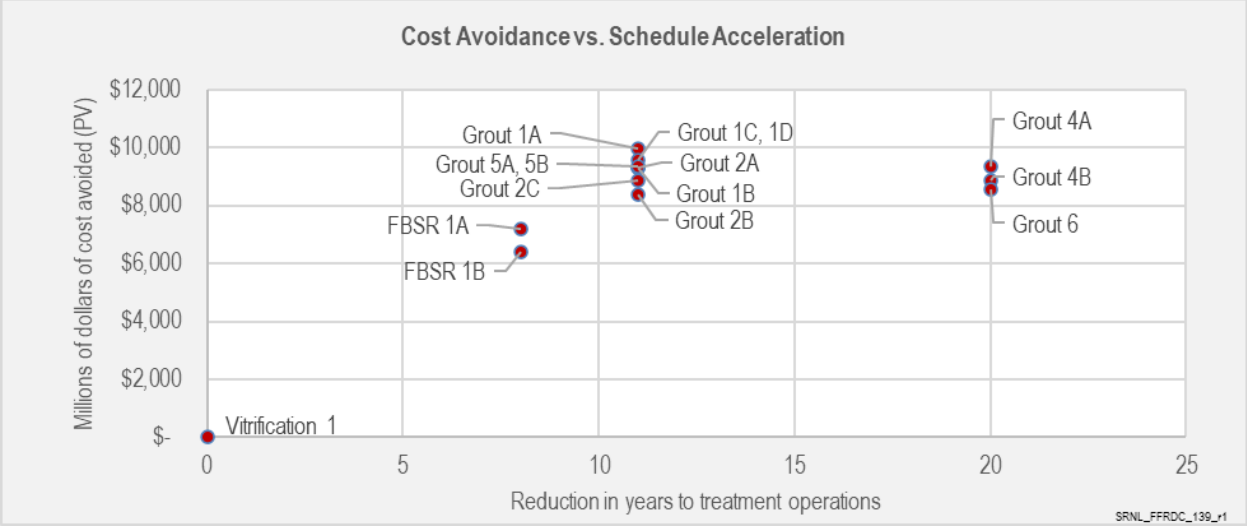


Figure 4.3-11. Tradeoff of Cost Avoidance vs. Schedule Acceleration, Start of Supplemental Treatment

For Criteria 5 and 6, the FFRDC team concluded that decision-makers should have the benefit of this and other analyses (e.g., by NASEM, GAO) prior to formulating input as part of the decision-making process. Likewise, securing regulatory approval is part of the negotiation process between government agencies, and it would be inappropriate for the FFRDC team to assign likelihood of specific outcomes. These criteria are included in the taxonomy but not included in the roll-up with the other criteria.

5.0 RESULTS USING THE DECISION FRAMEWORK

The FFRDC team used the top-tier criteria assessments to directly compare alternatives. Table 5-1 includes a high-level summary of results that can serve as a decision framework for decision-makers to inform their decisions regarding supplemental LAW treatment technologies and disposal locations. The table includes representative alternatives for each technology.

Table 5-1. High-Level Comparison of the Four Selected Alternatives for Supplemental Treatment of Low-Activity Waste

Alternative			
Vitrification 1: Disposal onsite at Hanford	**FBSR 1A: Solid monolith product disposal onsite at Hanford**	**Grout 4B: Off-site grouting/disposal**	**Grout 6: Phased Approach Off-site grouting/ disposal, then on-site grouting/disposal**
Criterion 1: Long-term effectiveness (environmental and safety risk after disposal)			
Highly effective for primary waste; moderately effective for secondary waste. Medium confidence in the assessment.	Effective. Medium confidence in the assessment, due to technology immaturity.	Highly effective. High confidence in the assessment.	Highly effective. Good to high confidence in the assessment.
Criterion 2: Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)			
High risk due to significant cost-based startup delays and operations limits. Moderate technical implementation risk. Construction finishes and treatment starts in 2047, mission does not complete without significant additional annual budget.	High risk due to construction time required and technical execution risk. Construction finishes and treatment starts in 2039; mission completes 2070.	Low risk due to earliest potential start of treatment in 2027, minimal construction, low-temperature process, likely capacity, and modest transportation and operations costs. Limited facilities (e.g., evaporator and load-out station) needed; mission completes 2066.	Very low risk due to earliest start of treatment in 2027, flexible timing of conversion to on-site low-temperature process, and inexpensive operations. Grout plant construction finishes 2039; mission completes 2066.
Criterion 3: **Likelihood of successful mission completion** (including technical, engineering, and resource-related risks)			
Very low probability of successful completion due to resource intensity.	Low probability of successful completion, due to technical risk.	Very high likelihood of successful completion.	High likelihood of successful completion.
Criterion 4: Lifecycle cost (discounted present value)			
$7.6B construction; $5.1B operations (total operations costs exceed benchmark budget by $1.2 B)	$3.4B construction; $2.2B operations	$0.4B construction; $3.4B operations	$1.4B construction; $2.7B operations

FBSR = fluidized bed steam reforming.

Alternative Vitrification 1 has a very low likelihood of mission completion because both peak estimated construction costs and estimated annual operating costs significantly exceed the benchmark budget, and this finding is not sensitive to the exact budget assumed. The cumulative shortfall for operations, relative to the benchmark budget, has a present value of $1.2 billion. Vitrification 1 is the only alternative that was found to consistently exceed the benchmark in all sensitivity cases, and is assessed as least likely to complete as designed. Vitrification 1 also has a longer delay until the start of operations compared to other alternatives, with supplemental treatment of LAW beginning in 2050. The delayed completion of construction and the length of operations increase environmental risk associated with the degradation of the waste storage tanks. The vitrified waste is expected to be highly effective in the long-term; however, the secondary waste produced by vitrification, which will be disposed of onsite, is expected to be only moderately effective.

The present value of lifecycle costs is $12.7 billion for Vitrification 1, which is more than twice the present value of lifecycle costs of FBSR 1A and more than three times greater than the present value of lifecycle costs of Grout 4B or 6.

Alternative FBSR 1A also has a low likelihood of mission completion, but due to technical risk, as FBSR is considered a first-of-a-kind technology for Hanford LAW and carries a great deal of uncertainty in the treatment process. The low technical maturity necesitates testing and development not required for the vitrification and grout alternatives, which contributes to delaying construction completion until 2039 and increases environmental risks related to storage tank degradation. While the FBSR waste form is expected to have acceptable long-term effectiveness, there is less confidence relative to the Vitrification 1 and Grout 4B and 6 waste forms.

Alternatives Grout 4B and Grout 6 have very high and high likelihoods of successful completion, respectively. While both have less construction and lower annual costs when compared to the vitrification and FBSR alternatives, Grout 4B construction is limited to an evaporator and loading facilities, while Grout 6 eventually constructs a grout plant. Both Grout 4B and 6 start treatment by an off-site vendor in 2027 and complete operations in 2065, thus reducing environmental risks related to storage tank degredation and have low and very low risks, respectively, with Grout 6 risk being lower due to the availability of two treatment options and the flexibility to delay grout plant construction. Both are highly effective with regard to long-term performance of the waste form, with a slight advantage to Grout 4B for all waste disposed of at an off-site location. The first phase of Grout 6 results in a large inventory of technetium and iodine being disposed of offsite. By the time this hybrid alternative shifts to on-site disposal, the technetium and iodine concentrations are expected to be much lower than those in the grouted secondary waste of Vitrification 1, which concentrates radionuclides in a smaller volume than the grout alternatives. Grout 6 is therefore expected to be more effective for long-term performance than Vitrification 1.

A risk with respect to out-of-state treatment/disposal options is the possibility that the resulting LAW might not be acceptable to the receiving facility – or to the regulatory authorities of transit or receiving states – and accordingly cannot be shipped from Hanford or returned to Hanford with no disposal path. As discussed in Volume I, Appendix D, and Volume II, Appendix H, all shipments to these two sites will need to meet all NRC and U.S. Department of Transportation requirements with which DOE and its contractors have extensive experience. At present, both the Waste Control Specialists (Andrews, Texas) and Energy*Solutions* (Clive, Utah) treatment/disposal sites are licensed to receive Class A waste, and 83 to 93% of grouted Hanford tank supplemental LAW is projected to fall within Class A (Volume II, Appendix H, Table H.3). Accordingly, the majority of the tank LAW likely meets the current waste acceptance criteria at both facilities and any state-imposed permit conditions.

The decision-informing criteria and the detailed criteria taxonomy appear in Volume I, Appendix A, and the details of the assessment of these four alternatives are provided in Volume I, Appendix B and Appendix C.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Several overarching observations and conclusions result from analysis of the alternatives:

1. Only grout-based alternatives allow the near-term disposition of LAW that achieves the fastest reduction of risk of future tank leaks. FBSR and vitrification do not allow the near-term supplemental treatment of LAW. There is a range of more than two decades in start-up schedules for the three technologies.
2. Processing flexibility for LAW is an important consideration. Flexibility is manifested through (1) the range in processing rates that the selected technology can readily achieve to accommodate disruptions, increases, and decreases in LAW processing; (2) the availability of different treatment technologies to adapt to variabilities and uncertainties in LAW characteristics; and (3) avoidance of single-point failure mechanisms (e.g., only having a single treatment facility or disposal facility vailable). If a technology other than vitrification is selected, vitrification will still be available through the WTP LAW Vitrification Facility for any wastes that are not amenable to that supplemental treatment process.
3. Grout alternatives are clearly executable at benchmark funding levels and have the highest probability of successful completion. FBSR alternatives might be executable within the benchmark budget but carry first-of-a-kind technical risks for Hanford LAW disposition. FBSR has higher annual cost and higher technical risk than grout and lower probability of successful completion. Vitrification, as a supplemental treatment of LAW, has a lower probability of successful implementation as it would be significantly more expensive than the other technologies in both annual and total funding needed.
4. The vitrification and grout alternatives provide long-term protectiveness of human health and the environment and can meet anticipated federal performance standards addressed by the first of the top-tier criteria with high confidence. Some alternatives may be capable of better performance than others, but all can meet existing and anticipated standards.
5. FBSR is a first-of-a-kind technology for the waste chemistry of Hanford LAW and thus, uncertainties in process and waste form performance, cost, and schedule are higher for alternatives using this technology than the grout and vitrification alternatives.
6. Off-site disposal eliminates the concern regarding potential additional impacts to Hanford groundwater and the Columbia River from the on-site disposal of non-vitrified LAW.
7. Off-site disposal at licensed LLW facilities outside of the state of Washington can result in removing ~70% of the inventory of ^{99}Tc, ^{129}I, and nitrates. Evaluation of the projected supplemental LAW feed vectors indicates that when grouted, ~83–93% of the pretreated LAW will meet NRC technical requirements for Class A LLW and waste acceptance criteria at NRC-licensed disposal facilities outside of the state of Washington. The remainder will meet the Class B or C criteria. For the FBSR alternative, ~72% of the waste forms will be Class A, with the remainder meeting the Class B or C criteria.
8. The AEA solely grants authority to DOE to determine whether tank waste is HLW. DOE will classify the Hanford tank waste after retrieval and treatment, in accordance with DOE O 435.1. Out of an abundance of caution, DOE conservatively manages the waste in the Hanford tanks as HLW until retrieval and treatment. The preamble to the RCRA LDR regulations requiring vitrification of HLW makes clear that the intended applicability of the vitrification method is only to the high-activity fraction of tank waste determined to be HLW and not to the low-activity fraction (LAW), and that solidification/stabilization by grout can be an acceptable approach for LAW (55 FR 22626-27).

However, in delegation of RCRA implementation authority to the state of Washington, the state is granted broad discretion over regulatory flexibility and can be more restrictive than federal standards as part of RCRA implementation. In an analogous situation of regulation by multi-agency regulation of DOE and commercial MLLW under RCRA, EPA promulgated a rule providing a conditional exemption from RCRA regulation; the rule grants sole regulatory authority over transportation and off-site disposal of exempted low-level mixed waste (LLMW) to the NRC (66 FR 27217, "Storage, Treatment, Transportation, and Disposal of Mixed Waste").[42]

9. A decision on the supplemental LAW treatment technology is needed as early as possible, and technical maturation activities to be accomplished need to be identified to achieve supplemental LAW treatment operational capability to meet the WTP high-activity fraction processing schedule needs and to accelerate waste storage risk reduction. If the supplemental LAW treatment facility is not ready when needed, tank waste treatment could be delayed, thus extending tank waste storage duration (and resulting in increased storage integrity and waste leakage risks).
10. Detailed evaluation of all six of the high-level criteria according to the taxonomy can be used as a framework for evaluation by decision-making authorities.

6.2 Recommendation(s)

DOE should expeditiously secure and implement multiple pathways for off-site grout solidification/ immobilization and disposal of LAW in parallel with the DFLAW vitrification process.

Recommendation Discussion

Following completion of the assessment of each alternative against top-tier decision Criteria 1 through 4, the FFRDC team sought to use the results of that process to support development of a recommendation using the following framing assumptions:

- In the absence of consensus of the FFRDC team, no recommendation would be made.
- Potential tradeoffs against Criteria 5 and 6 would not be taken into account. Any recommended alternative would reflect the team's consensus highest-value approach, for consideration by DOE and Congress in future negotiations and planning, with respect to the decision factors captured in Criteria 1 through 4.
- Every alternative that survived the screening process was assessed as "moderately effective with moderate uncertainty" or better against Criterion 1. In effect, every alternative was assessed as accomplishing the supplemental LAW treatment mission if successfully completed. As a result, Criterion 1 assessed levels had less influence than Criteria 2 through 4 in determining which alternative, if any, to recommend.
- During the assessment process, the FFRDC team identified additional processing options and variants not included in the defined set of alternatives. A traditional Analysis of Alternatives would restrict any recommendations to the set of fully assessed alternatives. However, the team agreed that it would be acceptable and informative to decision-makers to include a recommendation that may not reflect a fully assessed alternative.

[42] It is recognized that Washington State has not adopted 40 CFR 266, "Standards for the Management of Specific Hazardous Wastes and Specific Types of Hazardous Waste Management Facilities," Subpart N, "Conditional Exemption for Low-Level Mixed Waste Storage, Treatment, Transportation, and Disposal."

In weighing tradeoffs among criteria, given the assessed qualitative levels for each alternative, the team agreed that the differences in execution schedule among the alternatives, as captured in Criterion 2, should carry the most influence in the selection of a recommended alternative. Differences in probability of successful project completion were assessed as the next-most important differences across the four selected alternatives.

Given these judgments, only Alternatives Grout 4B and Grout 6 were candidates to be the single recommended alternative from the defined list. Comparing these two alternatives, the team considered the benefits of an early start and additional flexibility of future operations for Grout 6, versus a slightly higher probability of success and extra certainty in long-term performance for Grout 4B. The team consensus is that the benefits of the Grout 6 early start and execution flexibility to transition from off-site solidification/immobilization and disposal are decisive. The team chose to recommend the earliest possible initiation of off-site disposition, regardless of whether Alternative Grout 4B or Grout 6 (or a future variant) would be employed to complete the mission. That decision can be made at a later date, with the benefit of experience and technology maturation. The intent of multiple pathways is to provide parallel contractual agreements with multiple facilities for off-site solidification/immobilization and disposal to minimize risks associated with potential facility- or state-specific implementation challenges.

This recommended approach can provide many benefits:

- Provides the capability to achieve the most rapid reduction in the amount of waste stored in the Hanford SSTs and DSTs by using available off-site solidification/immobilization and disposal capacity, and therefore results in the most rapid reduction in risk to human health and the environment attributed to potential future unplanned tank waste releases.
  - DST capacity is available earlier to support waste retrievals and provides greater flexibility for HLW processing options.
  - Earlier available DST capacity provides defense-in-depth for recovery operations if future waste storage tank leaks are identified.
  - This approach can further enable optimized retrieval sequencing to reduce environmental and human health risk most rapidly.
- Provides additional long-term environmental protection, including to the aquifers underlying the Hanford Site and the Columbia River, by disposing of a significant portion of the inventory of risk-driving constituents (e.g., ^{99}Tc, ^{129}I) at off-site facilities that are located in geologic settings with low infiltration and do not have credible pathways to potable water aquifers.
- Provides flexibility in the available treatment technologies and disposal pathways, and reduces the potential for individual choke points to further delay the Hanford tank waste treatment and disposal mission. Concurrent LAW vitrification and solidification/immobilization treatment and disposal pathways would allow LAW routing based on waste characteristics to the most appropriate and efficient treatment technology.
- Mitigates the risk of having LAW with no disposal path by having multiple licensed off-site disposition facilities available to receive Hanford LAW. Further mitigation measures include:
  - Sampling and analyzing the waste first to ensure compatibility with the immobilization process
  - Ensuring that any waste deemed incompatible with the immobilization process is directed to LAW vitrification

  - Ensuring that both off-site permits/permit modifications (if any are needed), and agreements with off-site facilities, are in place prior to initiation of any on-site grouting or any shipment of liquid LAW for off-site treatment/disposal. Such agreements could ideally provide for alternative off-site contingency disposition arrangements in the event that the contracted receiving facility cannot disposition the waste as expected.

  The transport and disposal of liquid LLW has been performed by DOE multiple times, and is not unprecedented (see Volume II, Appendix D, Section D.3.7). In the very unlikely event that both off-site disposal facilities become permanently unavailable, DOE would need to explore several potential approaches, such as: (1) pursue identification of other locations that could accept this waste, (2) continue to work with state regulators and stakeholders to identify viable solutions, and/or (3) pursue application of new and emerging technologies and approaches for disposition of supplemental LAW.

- Enables the rapid start of LAW grout processing and allows time to understand the performance of the DFLAW vitrification process and mature technologies necessary to transition to other disposition approaches for the remaining LAW if desired (e.g., on-site treatment, on-site disposal). For example, a highly instrumented limited pilot demonstration of on-site disposal of grouted LAW, after a decade, could reduce uncertainties of grouted LAW performance and inform future on-site treatment and disposal decisions.
- Provides potential to reduce or eliminate the need for future additional treatment capability and affords time to make such decisions.
- Minimizes financial demands by reducing mission duration and lifecycle costs.
- Offers an approach with high likelihood of successful implementation and mission completion.

This recommendation does not reflect a specific alternative from this analysis because of implementation uncertainties. Elements of specific alternatives were beneficial to inform the alternatives analysis process; however, specific details for implementation of this recommendation will need to be identified through DOE processes, multi-party negotiations, and the NEPA process.

If the recommendation is accepted, the regulatory, stakeholder, and tribal treaty aspects will need to be addressed using established formal processes.

Regulatory Elements

The necessary permits and authorizations will need to be obtained by DOE, including use of the NEPA process to implement the resulting program. Off-site disposal viability was based on review of approved current disposal site waste acceptance criteria and transportation regulations and requirements.

Stakeholder Elements

Stakeholder and community input will be collected and analyzed through DOE's existing agreements, policies, and procedures, including the NEPA process, to inform its decision-making process.

Tribal Treaty Aspects

To address Tribal Nations' treaty rights at the Hanford Site, DOE conducts government-to-government interactions with Tribes and fulfills the trust responsibility of the United States to protect tribal sovereignty and self-determination, tribal lands, assets, resources, and tribal treaty, and other federally recognized and reserved rights, pursuant to DOE O 144.1.

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Appendix A. Decision-Informing Criteria

A.1 CRITERIA PROVIDED BY CONGRESS

Section 3125 of the Fiscal Year (FY) 2021 National Defense Authorization Act (NDAA21), directs the U.S. Department of Energy (DOE) to have a Federally Funded Research and Development Center (FFRDC) conduct a follow-on analysis to the analysis required by Section 3134 of the National Defense Authorization Act for FY 2017 (NDAA17) and develop a framework that would help decision-makers decide among treatment technologies for supplemental treatment of Hanford low-activity waste (LAW), associated waste forms, and disposal locations for the waste. This appendix describes the rationale behind the identification of primary decision-informing criteria to be assessed by the FFRDC team, and the details of the taxonomy of subsidiary (lower-tier) criteria and analyses supporting those criteria.

Section 3125 also lists specific factors and criteria that the FFRDC team should address in their assessment of the alternatives. The elements include:

"1. The most effective potential technology for supplemental treatment of LAW that will produce an effective waste form, including an assessment of the:
   a. Maturity and complexity of the technology
   b. Extent of previous use of the technology
   c, Lifecycle costs and duration of use of the technology
   d. Effectiveness of the technology with respect to immobilization
   e. Performance of the technology expected under permanent disposal.

2. The differences among approaches for the supplemental treatment of LAW considered as of the date of the FFRDC team analysis.

3. The compliance of such approaches with the technical standards described in Section 3134(b)(2)(D) of the NDAA17.

4. The differences among potential disposal sites for the waste form produced through such treatment, including mitigation of radionuclides, including technetium-99, selenium-79, and iodine-129, on a system level.

5. Potential modifications to the design of facilities to enhance performance with respect to disposal of the waste form to account for the following:
   a. Regulatory compliance
   b. Public acceptance
   c. Cost
   d. Safety
   e. The expected radiation dose to maximally exposed individuals over time
   f. Differences among disposal environments.

6. Approximately how much and what type of pretreatment is needed to meet regulatory requirements regarding long-lived radionuclides and hazardous chemicals to reduce disposal costs for radionuclides described in item 4 above.

7. Whether the radionuclides can be left in the waste form or economically removed and bounded at a system level by the performance assessment of a potential disposal site and, if the radionuclides cannot be left in the waste form, how to account for the secondary waste stream.

8. Other relevant factors relating to the technology […], including the following:
   a. The costs and risks in delays with respect to tank performance over time
   b. Consideration of experience with treatment methods at other sites and commercial facilities
   c. Outcomes of the Test Bed Initiative of the DOE Office of Environmental Management at the Hanford Nuclear Reservation."

In terms of stakeholder values, these elements include a mix of fundamental goals (e.g., safety and effectiveness with respect to immobilization), types of evidence (e.g., extent of previous use, findings from the Test Bed Initiative, and experience with treatment methods at other sites), and contributing risk factors (e.g., expected dose and differences among disposal sites).

A.2 SELECTION CRITERIA TEMPLATE

The following criteria were developed for review of the alternatives.

Decision-Informing Criteria Assessment Template

1. Long-term effectiveness
(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion
Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply were screened out.

1.1.1. Residual toxicity of wastes

1.1.1.1. Nitrates/nitrites

1.1.1.2. RCRA metals: No reduction in inherent toxicity; No measure of effectiveness (MOE) needed since all are equivalent.

1.1.1.3. LDR organics:

1.1.1.4. Ammonia

1.1.1.5. Greenhouse gas emissions
No expected difference in residual carbon footprint across alternatives.

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides
MOE: Estimated concentration over ~1,000 years (to DOE O 435.1); delay to peak is when peak occurs and differs between scenarios; identify peak to 10,000 years for information only (i.e., compliance vs. post-compliance periods).

1.1.2.1.1. Iodine

1.1.2.1.2. Technetium-99 (^{99}Tc)

1.1.2.1.3. Selenium-79 (^{79}Se)

1.1.2.1.4. Cesium and strontium
Cesium and strontium half-lives make them a pre-completion issue; no MOE needed here.

1.1.2.2. Nitrates/nitrites

1.1.2.3. Ammonia

1.1.2.4. RCRA metals
MOE: Leachate Toxicity Characteristic Leaching Procedure (TCLP) compliance.

1.1.2.4.1. Mercury

1.1.2.4.2. Chromium

1.1.2.4.3. Other

1.1.3. Total volume of primary and secondary waste forms

1.2. Long-term risks upon successful completion

MOE: Error bars in 1.1. Estimates above vs. margin under health/regulatory standards.

1.2.1. Confidence in estimated residual toxicity

1.2.1.1. LDR organics/destruction of organics

1.2.1.2. Nitrates/nitrites

1.2.1.3. Ammonia/ammonium ion.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury

1.2.1.4.2. Chromium

1.2.1.4.3. Other RCRA metals

1.2.2. Confidence in immobilization with regard to groundwater

1.2.2.1. Iodine

1.2.2.2. Technetium (including non-pertechnetates)

1.2.2.3. ^{79}Se

1.2.2.4. Nitrates/nitrites

1.2.2.5. Ammonia/ammonium ion

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury

1.2.2.6.2. Chromium

1.2.2.6.3. Other RCRA metals

1.2.3. Confidence in total volume of primary and secondary waste forms produced

2. <u>Implementation schedule and risk</u>

<u>(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)</u>

2.1. Specific risks or benefits related to ongoing tank degradation

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

2.2.1.1. Radiation

2.2.1.2. Chemical exposure

2.2.1.3. Particulate exposure

2.2.1.4. Physical injury

2.2.2. Transportation risks

MOE: Number and distance of trips, health risks of material being transported.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

2.3.2. Atmospheric discharges

2.3.3. Transfer/process tank (on-site) spills

2.3.4. Off-site transportation spills

2.3.5. Secondary waste streams generated

2.3.6. Greenhouse gas emissions

2.4. Duration

2.4.1. Duration to hot startup (years from decision)

2.4.2. Duration to full capacity (additional years)

2.4.3. Duration of operations (additional years)

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues

2.4.4.2. Delay due to annual operating costs exceeding budget

3. Likelihood of successful mission completion
(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risks of things that would stop the project before completion

3.1.1.1. Technology/engineering failure modes (alternative-specific)

3.1.1.1.1. [Failure mode #1 with likelihood]

3.1.1.1.2. [Failure mode #2 with likelihood]

3.1.1.1.3. [Failure mode #3 with likelihood]

3.1.1.1.4. …

3.1.1.2. Process complexity
Considers static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, required chemicals added, etc.

3.1.1.2.1. Unit operations (alternative-specific)

3.1.1.2.2. Accuracy of controls needed

3.1.1.2.3. Commercially available/"of a type"/bespoke systems

3.1.1.2.4. Overall flowsheet integration complexity

3.1.1.3. Required facilities/infrastructure

3.1.1.4. Required demolition/removal/modification

3.1.1.5. Technology maturity (including Test Bed Initiative)

MOE: Technology readiness levels for critical technology elements.
MOE: Demonstrated effectiveness elsewhere (including Test Bed Initiative).
MOE: Analogous DOE experience.

3.1.2. Robustness to known technical risks
(ability to recover from failure modes listed above)

3.1.2.1. Process and equipment robustness

3.1.2.2. Recovery from unexpectedly poor waste form performance

3.1.3. Adaptability to the full range of tank waste compositions

3.1.4. Potential to incorporate future technology advances

3.2. Likelihood and consequences of failing to complete due to resource constraints

3.2.1. MOE: Average annual spending vs. benchmark budget.

3.2.2. MOE: Projected peak spending vs. benchmark budget.

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget
MOE: Ability to start and stop operations in response to external factors.

3.2.4. Expected work remaining at failure point

3.2.5. Worst case (plausible) work remaining at failure

3.3. Likelihood and consequences of failing to complete due to unavailability of key services or materials

4. Lifecycle Costs
(discounted present value)

4.1. Capital project costs (Design plus facility construction and cold commissioning)

4.2. Operations costs

4.3. Shutdown and decommissioning costs

5. Securing and Maintaining Necessary Permits/Authorities
(regulatory approval)

6. Community/Public Acceptance (state, local)

With respect to Criteria 5 and 6, the FFRDC team concluded that the public should have the benefit of this and other analyses (e.g., by National Academy of Sciences, Engineering, and Medicine [NASEM] and U.S. Government Accountability Office [GAO]) prior to formulating their inputs to the decision-making process. Likewise, securing regulatory approval is part of the negotiation process between government agencies, and it would be inappropriate for the FFRDC team to estimate the likelihood of specific outcomes. These criteria are included in the taxonomy for completeness but were not assessed as part of the evaluations of individual alternatives. However, where there are significant observations, issues, or uncertainties with respect to Criteria 1 through 4 of the Assessment Template that are potentially relevant to regulation or stakeholder acceptance of specific alternatives, these are addressed in the accompanying discussion of that alternative in Volume II, Appendix C and Appendix E.

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Resource Conservation and Recovery Act of 1976, 42 USC 6901, et seq.

Appendix B. Summary of Selection Criteria Data for Four Selected Alternatives

B.1 INTRODUCTION

This appendix provides summaries of the following four alternatives discussed in Section 3.0 of the report:

- **Vitrification 1** – Vitrification with on-site disposal at Hanford
- **FBSR 1A** – Fluidized bed steam reformed solid monolith product with on-site disposal at Hanford
- **Grout 4B** – Grouting performed by an off-site vendor with off-site disposal
- **Grout 6** – Phased off-site grouting and disposal, then on-site grouting and disposal in containers.

This appendix is a shortened version of the full Alternative Selection Criteria provided in Volume II, Appendix D for these four alternatives. It is not intended to replace the full Alternative Selection Criteria but is provided as a version that is easier to compare between alternatives. The text for each description is derived from but not identical to the longer criteria sections.

In the tables below, the green descriptors indicate a positive attribute of that alternative, the red descriptors indicate a negative attribute of the alternative. The few brown descriptors are items that are not negative attributes at this time, but could become a negative attribute, depending on the outcome of future activities.

Volume II, Appendix C provides an overview of each of the technologies and their assumptions, with schematics depicting the building blocks of each alternative.

B.1.1 Alternative Vitrification 1, Single Supplemental Low-Activity Waste Vitrification Plant

Alternative Vitrification 1		
1. Long-term effectiveness (environmental and safety risk after disposal)		
1.1 Residual threat to health and environment upon successful completion	1.1.1 Residual toxicity of wastes	Nitrate/nitrite are destroyed in the melter/offgas system. There is some uncertainty about the residual toxicity/long-term performance of secondary wastes.
	1.1.2 Mobility of primary and secondary wastes to a groundwater source	Large amount of ammonia from melter reactions is present in the secondary waste disposed of at the Integrated Disposal Facility (IDF) in a grout waste form and its long-term behavior is not well understood. ^{129}I is semi-volatile and its partitioning to the secondary streams and performance in secondary wastes after disposal in IDF carries moderate uncertainty. There is low mobility of radionuclides and hazardous metals in the glass waste form with respect to groundwater.
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste form is smallest. Total volume of secondary liquid waste is largest; likely requiring expansion of the Effluent Treatment Facility (ETF). Largest volume of secondary solid waste.
1.2 Long-term risks upon successful completion	1.2.1 Confidence in estimated residual toxicity	Expect destruction of most organics in the waste by melter/plenum. There is uncertainty in the organic speciation and behavior during vitrification and the quantity of hazardous organics produced by the melter (e.g., acetonitrile) and their fate in downstream processing. Mercury – Low confidence that partitioning will be as expected; mercury is highly volatile and notoriously distributed in multiple offgas system components. High confidence that most Resource Conservation and Recovery Act (RCRA) metals (except mercury) are mostly retained in glass waste form by recycling the offgas condensate.

Alternative Vitrification 1		
	1.2.2 Confidence in immobilization with regard to groundwater	Low confidence in ^{129}I speciation/partitioning/retention in secondary wastes. High confidence in technetium partitioning during operations and level of retention in glass. Uncertainty of ^{99}Tc behavior during melter idling where it extensively vaporizes and distributes to the offgas system components. High confidence in low groundwater impact of ^{129}I or ^{99}Tc from disposed primary waste in IDF due to stability of glass waste form. Moderate uncertainty in ^{129}I and ^{99}Tc long-term immobilization in stabilized secondary wastes with or without getters (for iodine) are used. High confidence in nitrate/nitrite destruction. Low confidence in ammonia behavior in grouted secondary waste. High confidence in immobilization and limited impact to groundwater for all contaminants of concern (CoC) during the 1,000-year compliance period based on contemporary assessments.
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in volume of primary waste form. Moderate confidence in secondary waste form volume.
2. Implementation schedule and risks (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)		
2.1 Specific risks or benefits related to ongoing tank degradation		Delayed start-up of processing due to high costs and complex construction, which will delay retrieval of wastes from tanks, allowing more time for further degradation and potential future leaks. Consumption of entire budget would prevent early start up or alternate processing.
2.2 Risks to Humans (other than tank degradation)	2.2.1 Effort required to ensure worker safety	Challenging to mitigate risk of contamination due to volatility of radionuclides and hazardous species that distribute to offgas components, high maintenance requirements, and fly-wheeling of radionuclides. Challenging to mitigate risk of chemical exposure: high maintenance requirements of melter and offgas system, hazardous chemicals (e.g., liquid ammonia), resulting in 38 high-hazard consequences for workers identified. Two medium consequence public hazards.
	2.2.2 Transportation risks	Low transportation risks.
2.3 Risks to the Environment (other than tank degradation)	2.3.1 Wastewater discharges	High volume of wastewater discharges likely requiring new/expanded ETF. ^{129}I fate in offgas and secondary wastes is unconfirmed.
	2.3.2 Atmospheric discharges	High atmospheric discharges (38 MT constituents of potential concern [CoPC] per 1 Mgal of waste treated).
	2.3.3 Transfer/process tank (on-site) spills	Low on-site and off-site transportation spills.
	2.3.4 Off-site transportation spills	Low risk.
	2.3.5 Secondary waste streams generated	High quantity of secondary waste streams generated.
	2.3.6 Greenhouse gas emissions	High greenhouse gas emissions (1.5 Mgal fuel, 74 GWh electricity, and 570 deliveries per 1 Mgal of waste treated).

Alternative Vitrification 1		
2.4 Duration	2.4.1 Duration to hot startup	Expect ~25 years to construct.
	2.4.2 Duration to full capacity	Expect 3 years to ramp up all melters to capacity.
	2.4.3 Duration of operations	Extended duration due to late start and slow ramp up to full capacity.
	2.4.4 Risk of additional delay	Moderate risk of delay due to technical issues due to mitigation based on lessons learned from first low-activity waste (LAW) melters. High risk of delay due to annual operating costs exceeding budget.
3 Likelihood of successful mission completion (including technical, engineering, and resource-related risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Low likelihood of failure – First LAW melters will inform design/operations. Low risk of failure to corrosion, fire, release of radionuclides, control of the wet electrostatic precipitator (WESP). Highly complex and integrated system causing operation challenges. Extensive controls needed – Sampling/analysis, modeling. Many one-of-a-kind components. High overall flowsheet integration complexity. High number of required facilities/infrastructure/chemicals/utilities. Demonstrated effectiveness of Waste Treatment and Immobilization Plant (WTP) LAW melters will inform design/operations.
	3.1.2 Robustness to known technical risks	Robustness/adaptability – First LAW melters will inform design and operations, mitigating risk by the time the supplemental LAW melters begin operations.
	3.1.3 Adaptability to a range of waste compositions	Ability to adjust waste loading and glass-forming chemical recipe would permit adaptability.
	3.1.4 Ability to incorporate future advances	High capital cost and unique operations make incorporation of future advances challenging.
3.2 Likelihood & consequences of failing to complete due to resource constraints	3.2.1 Annual average spending	Funding needs would likely exceed the annual benchmark funding level.
	3.2.2 Projected peak spending	Peak funding needs would likely greatly exceed the annual benchmark funding level.
	3.2.3 Schedule flexibility	Low schedule flexibility; melters have limited ability to operate at varying rates due to need to maintain cold cap coverage.
	3.2.4 Expected work remaining at failure point	Unlikely that sufficient funds would be available to start up by need date.
	3.2.5 Worst plausible case work remaining at failure	Unlikely that sufficient funds would be available to start up by need date.
3.3 Likelihood and consequences of failing to complete due to unavailability of key services and materials		Numerous one-of-a-kind components and materials would be challenging to maintain over the extended operating life cycle duration. Extensive sample characterization may exceed analysis capacity and delay processing.
4. Life Cycle Costs (discounted present value)		
Total	(discounted)	$12,700 M

B.1.2 Alternative FBSR 1A, Fluidized Bed Steam Reforming Onsite Disposal

Alternative FBSR 1A		
1. Long-term effectiveness (environmental and safety risk after disposal)		
1.1 Residual threat to health and environment upon successful completion	1.1.1 Residual toxicity of wastes	Nitrate/nitrite and Land Disposal Restrictions (LDR) organics destroyed. Residual toxicity of secondary wastes – Mercury on granular activated carbon (GAC). No ammonia in final waste form. Iodine and technetium partition predominantly to primary waste.
	1.1.2 Mobility of primary and secondary wastes to a groundwater source	Low release of technetium and metals from granular product if structural incorporation occurs. Iodine performance in final waste form appears to be similar to technetium; however, there is greater uncertainty with long-term mobility reduction and uncertainties in structural incorporation.
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste is intermediate (~1.0×, including ~10% coal). No secondary liquid waste.
1.2 Long-term risks upon successful completion	1.2.1 Confidence in estimated residual toxicity	Destruction of all organics in denitration and mineralizing reformer (DMR) and/or thermal oxidizer (TO). Mercury – High confidence of partitioning to GAC. Moderate – High confidence in iodine partitioning to primary waste form. High confidence technetium and most RCRA metals are retained in granular product. High confidence non-pertechnetate destroyed and retained in granular product. High confidence in nitrate/nitrite destruction; no ammonia issues.
	1.2.2 Confidence in immobilization with regard to groundwater	High confidence in low groundwater impact of ^{129}I or ^{99}Tc and moderate-high confidence of ^{129}I IDF performance with projected incorporation and likely retention in and stability of the granular mineral product primary waste form; however, moderate uncertainty on the degree of incorporation. High confidence in nitrate/nitrite and ammonia destruction. High confidence in immobilization and limited impact to groundwater for all CoCs during the 1,000-year compliance period based on contemporary assessments.
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in total volume of primary and secondary waste forms.
2. Implementation schedule and risks (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)		
2.1 Specific risks or benefits related to ongoing tank degradation		Delayed start-up of processing due to high costs and complex construction, which would delay retrieval of wastes from tanks, allowing more time for further degradation and potential future leaks. Consumption of entire budget would prevent early startup or alternate processing.
2.2 Risks to Humans (other than tank degradation)	2.2.1 Effort required to ensure worker safety	Multiple hazards; 34 high-consequence worker hazards. One medium consequence public hazard. High risk of contamination from radioactive dust during maintenance. High risk of chemical exposure: high maintenance requirements. Hazardous chemicals, cryogenic liquids; steam.
	2.2.2 Transportation risks	Low transportation risks.

Alternative FBSR 1A		
2.3 Risks to the Environment (other than tank degradation)	2.3.1 Wastewater discharges	No wastewater discharges.
	2.3.2 Atmospheric discharges	Moderate-low atmospheric discharges (4 MT CoPCs per 1 Mgal waste treated).
	2.3.3 Transfer/process tank (on-site) spills	Low on-site transportation spills.
	2.3.4 Off-site transportation spills	Low off-site transportation spills.
	2.3.5 Secondary waste streams generated	Low amount of secondary waste streams generated.
	2.3.6 Greenhouse gas emissions	High greenhouse gas (200,000 gal fuel, 984 MT coal, 19 GWh, 416 deliveries per 1 Mgal waste treated).
2.4 Duration	2.4.1 Duration to hot startup	Expect ~15 years to construct. No potential for early start.
	2.4.2 Duration to full capacity	Expect 3 years to ramp up both units to capacity.
	2.4.3 Duration of operations	Delay to high-level waste (HLW) campaign because of slow/late startup of fluidized bed steam reforming (FBSR).
	2.4.4 Risk of additional delay	High risk of additional delay due to technical issues.
3 Likelihood of successful mission completion (including technical, engineering, and resource-related risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Moderate likelihood of failure – Fully integrated offgas system untested – baseline process moderate maturity with this waste/waste form. Low expected release of radionuclides – Not volatized. Highly complex and integrated system causing operation challenges. Extensive controls needed – Sampling/analysis, modeling. Several one-of-a-kind components. High overall flowsheet integration complexity. High number of required facilities/infrastructure/chemicals/utilities. Demonstrated effectiveness – First-of-a-kind for similar waste form.
	3.1.2 Robustness to known technical risks	Low robustness. Potential for delays.
	3.1.3 Adaptability to a range of waste compositions	Moderate adaptability.
	3.1.4 Ability to incorporate future advances	Challenging for redesign or process changes.
3.2 Likelihood & consequences of failing to complete due to resource constraints	3.2.1 Annual average spending	Funding needs would likely exceed the annual benchmark funding level.
	3.2.2 Projected peak spending	Peak funding needs would likely greatly exceed the annual benchmark funding level.
	3.2.3 Schedule flexibility	Moderate schedule flexibility.
	3.2.4 Expected work remaining at failure point	Unlikely that sufficient funds would be available to start up by need date.
	3.2.5 Worst plausible case work remaining at failure	Unlikely that sufficient funds would be available to start up by need date.

Alternative FBSR 1A		
3.3 Likelihood and consequences of failing to complete due to unavailability of key services and materials		Numerous one-of-a-kind components and materials. Single U.S. company technology supplier.
4. Life Cycle Costs (discounted present value)		
Total	(discounted)	$5,527 M

B.1.3 Alternative Grout 4B, Off-site Vendor for Grouting with Off-site Disposal

Alternative Grout 4B		
1. Long-term effectiveness (environmental and safety risk after disposal)		
1.1 Residual threat to health and environment upon successful completion	1.1.1 Residual toxicity of wastes	Nitrate/nitrite not destroyed (but inconsequential to off-site disposal). Treatment, if needed, lowers LDR organics in final waste form to beneath limits; volatile organics in secondary liquid waste treatable in ETF. Minimal ammonia in primary or secondary waste forms.
	1.1.2 Mobility of primary and secondary wastes to a groundwater source	Off-site disposal does not have a pathway to potable water due to geology.
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste is largest (1.8×). Secondary liquid volume from evaporator to ETF is moderate.
1.2 Long-term risks upon successful completion	1.2.1 Confidence in estimated residual toxicity	High confidence in absence or removal of all organics by evaporation/oxidation, if needed. High confidence in no change to toxicity of nitrate/nitrite and RCRA metals. High confidence ammonia would not be significant in grouted tank waste.
	1.2.2 Confidence in immobilization with regard to groundwater	Mercury – High confidence in ability to sequester in grout waste form. High confidence most RCRA metals are retained in grout waste form. No impact of inventory and behavior of technetium, non-pertechnetate, or iodine on Hanford groundwater. High confidence off-site disposal does not have a pathway to potable water due to geology.
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in predicted total of primary waste form (1.8×) and secondary liquid (~0.4×) waste and solid secondary waste form volume.
2. Implementation schedule and risks (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)		
2.1 Specific risks or benefits related to ongoing tank degradation		Lowest risk of additional tank leaks; HLW and retrievals could meet schedules. Alternative does not consume entire budget, providing opportunity for early start as part of hybrid or concurrent alternatives. High flexibility in tank utilization, transfer piping.

Alternative Grout 4B		
2.2 Risks to Humans (other than tank degradation)	2.2.1 Effort required to ensure worker safety	Low risk of contamination: no volatile radionuclides, low maintenance. Low risk of chemical exposure: low maintenance requirements. Minimal hazardous chemicals, zero high-hazard consequences for workers; 12 medium consequence worker hazards.
	2.2.2 Transportation risks	Moderate risk; high number of radioactive transports.
2.3 Risks to the Environment (other than tank degradation)	2.3.1 Wastewater discharges	Moderate amount of wastewater discharges (~0.4×), no new ETF needed. Minimal solid, moderate liquid secondary waste streams generated.
	2.3.2 Atmospheric discharges	Negligible atmospheric discharges of radionuclides or CoPCs.
	2.3.3 Transfer/process tank (on-site) spills	Low on-site transportation spill risk.
	2.3.4 Off-site transportation spills	Low off-site transportation spill risk.
	2.3.5 Secondary waste streams generated	Minimal secondary wastes generated.
	2.3.6 Greenhouse gas emissions	~30,000 gal fuel oil for evaporator boiler, 2.5 GWh electricity, 209 deliveries per 1 Mgal treated.
2.4 Duration	2.4.1 Duration to hot startup	Expect ~5 years (including construction of evaporator).
	2.4.2 Duration to full capacity	Vendors are available with immobilization capacity.
	2.4.3 Duration of operations	As needed to support HLW mission.
	2.4.4 Risk of additional delay	Minimal risk of delay (potential early start as part of hybrid; see alternative Grout 6).
3 Likelihood of successful mission completion (including technical, engineering, and resource-related risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Low likelihood that LDR organics are above limits or removal is inadequate. Minimal process complexity and integration. Minimal controls needed – Sampling/analysis, modeling. Commonly available components/equipment. Low overall flowsheet integration complexity. Low number of required facilities/infrastructure/chemicals/utilities. Cross-site supernate transfer line not needed to support this alternative. Demonstrated effectiveness with Hanford waste and off-site disposal in Test Bed Initiative.
	3.1.2 Robustness to known technical risks	High robustness/adaptability – Other site experience 20+ years.
	3.1.3 Adaptability to a range of waste compositions	High adaptability to accommodate feed variability. Alternative is to divert incompatible waste to WTP LAW vitrification.
	3.1.4 Ability to incorporate future advances	Readily incorporate future advances. Vendors are anticipated to have sufficient capacity, or could expand if needed, to meet demand (although some may require permit changes).

Alternative Grout 4B		
3.2 Likelihood & consequences of failing to complete due to resource constraints	3.2.1 Annual average spending	Funding needs would likely be well beneath the annual benchmark funding level. Likely that sufficient funds would be available to start up by need date.
	3.2.2 Projected peak spending	Peak funding needs would likely be well beneath the benchmark funding level.
	3.2.3 Schedule flexibility	Flexible process (e.g., simple shutdown, common construction methods).
	3.2.4 Expected work remaining at failure point	Likely that sufficient funds would be available to start up by need date.
	3.2.5 Worst plausible case work remaining at failure	Likely that sufficient funds would be available to start up by need date.
3.3 Likelihood and consequences of failing to complete due to unavailability of key services and materials		Grout production currently available from vendor(s). Disposal sites available (although only one for U.S. Nuclear Regulatory Commission [NRC] low-level waste [LLW] Class >A). Alternative sources of key materials may need development in long term.
4. Life Cycle Costs (discounted present value)		
Total	(discounted)	$3,854 M

B.1.4 Alternative Grout 6, Phased Off-site and On-site Grouting in Containers

Alternative Grout 6		
1. Long-term effectiveness (environmental and safety risk after disposal)		
1.1 Residual threat to health and environment upon successful completion	1.1.1 Residual toxicity of wastes	Nitrate/nitrite not destroyed (inconsequential during off-site disposal). If present, pretreatment lowers LDR organics in final waste form to beneath limits. Minimal ammonia in primary or secondary waste.
	1.1.2 Mobility of primary and secondary wastes to a groundwater source	Phases 1–2 (off-site disposal): Off-site disposal does not have a pathway to potable water due to geology. Phase 3 (on-site disposal): Getter for iodine (or vault disposal) and reduced inventory of iodine and technetium disposed of onsite expected to provide long-term mobility reduction.
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste is large (1.8×). Secondary liquid volume from evaporator to ETF is moderate. Very low secondary solid waste.
1.2 Long-term risks upon successful completion	1.2.1 Confidence in estimated residual toxicity	Low uncertainty in absence or removal of all organics by evaporation/oxidation, if needed. High confidence in no change to toxicity of nitrate/nitrite and RCRA metals. High confidence ammonia would not be significant in grouted tank waste. High confidence organics in secondary liquid waste absent or treatable.

Alternative Grout 6		
	1.2.2 Confidence in immobilization with regard to groundwater	Mercury – High confidence in ability to sequester in grout waste form. High confidence most RCRA metals are retained in grout waste form. Phases 1–2: No impact of inventory and behavior of technetium, non-pertechnetate, or iodine. High confidence off-site disposal does not have a pathway to potable water due to geology. Phase 3: High confidence in immobilization and limited impact to groundwater for all CoCs during the 1,000-year compliance period based on contemporary assessments. Moderate confidence in iodine getter performance beyond compliance period and long-term performance of grout.
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in predicted total of primary waste form (1.8×) and secondary liquid (~0.4×) waste and solid secondary waste volume.
2. Implementation schedule and risks (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)		
2.1 Specific risks or benefits related to ongoing tank degradation		Lowest risk of additional tank leaks; HLW and retrievals could meet schedules. Alternative is intended to consume entire budget, enabling early start and thereby reducing risk of leaks. Flexibility in tank utilization, transfer piping.
2.2 Risks to Humans (other than tank degradation)	2.2.1 Effort required to ensure worker safety	Low risk of contamination: no volatile radionuclides, low maintenance. Low risk of chemical exposure: low maintenance requirements. Minimal hazardous chemicals, zero high-hazard consequences for workers; 12 medium consequence worker hazards.
	2.2.2 Transportation risks	Moderate risk; high number of radioactive transports.
2.3 Risks to the Environment (other than tank degradation)	2.3.1 Wastewater discharges	Moderate amount of wastewater discharges (~0.4×), no new ETF needed. Minimal solid, moderate liquid secondary waste streams generated.
	2.3.2 Atmospheric discharges	Negligible atmospheric discharges of radionuclides or CoPCs.
	2.3.3 Transfer/process tank (on-site) spills	Low on-site transportation spill risk.
	2.3.4 Off-site transportation spills	Low off-site transportation spill risk.
	2.3.5 Secondary waste streams generated	Minimal secondary wastes generated.
	2.3.6 Greenhouse gas emissions	~30,000 gal fuel oil for evaporator boiler, 2.5 GWh electricity, 209 deliveries per 1 Mgal treated.
2.4 Duration	2.4.1 Duration to hot startup	Expect ~5 years to start up (including construction of evaporator) for Phase 1.
	2.4.2 Duration to full capacity	Vendors are available with immobilization capacity for Phase 1.
	2.4.3 Duration of operations	As needed to support HLW mission for Phases 2–3.
	2.4.4 Risk of additional delay	Minimal risk of delay.

Alternative Grout 6		
3 Likelihood of successful mission completion (including technical, engineering, and resource-related risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Low likelihood that LDR organics are above limits or that removal inadequate, if needed. Minimal process complexity and integration. Minimal controls needed – Sampling/analysis, modeling. Commonly available components/equipment. Low overall flowsheet integration complexity. Low number of required facilities/infrastructure/chemicals/utilities. Cross-site supernate transfer line not needed to support this alternative. Demonstrated effectiveness for Phase 1 with Hanford waste and off-site disposal in Test Bed Initiative.
	3.1.2 Robustness to known technical risks	High robustness/adaptability – Other site experience 20+ years.
	3.1.3 Adaptability to a range of waste compositions	High adaptability to accommodate feed variability. Alternative is to divert incompatible waste to WTP LAW vitrification.
	3.1.4 Ability to incorporate future advances	Readily incorporate future advances. Vendors are anticipated to have sufficient capacity or could expand capacity, if needed, to meet demand (although some may require permit changes).
3.2 Likelihood & consequences of failing to complete due to resource constraints	3.2.1 Annual average spending	Funding intended to match the annual spending benchmark. Likely that sufficient funds would be available to start up by need date.
	3.2.2 Projected peak spending	Peak funding needs would likely be within the annual benchmark funding level.
	3.2.3 Schedule flexibility	Flexible process (e.g., simple shutdown, common construction methods).
	3.2.4 Expected work remaining at failure point	Likely that sufficient funds would be available to start up by need date.
	3.2.5 Worst plausible case work remaining at failure	Likely that sufficient funds would be available to start up by need date.
3.3 Likelihood and consequences of failing to complete due to unavailability of key services and materials		Grout production currently available from vendors. Disposal sites available (only one for NRC LLW Class >A) for Phases 1-2. Alternative sources of key materials may need development in long term.
4. Life Cycle Costs (discounted present value)		
Total	(discounted)	$4,127 M

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Appendix C. Selection Criteria Assessments for Four Selected Alternatives

C.1 INTRODUCTION

The decision-informing criteria described in Volume I, Appendix A were developed as assessment measures for the alternatives evaluated in this report. Each alternative was assessed against the criteria by a sub-team of subject matter experts on the Federally Funded Research and Development Center (FFRDC) team. Where applicable, this expert team reviewed previously developed technical reports to identify information to support each assessment. In the absence of specific technical information regarding specific criteria, expert judgement from related work and experience was used to inform the assessment.

C.2 SELECTION CRITERIA ASSESSMENTS – FOUR SELECTED ALTERNATIVES

The criteria for each alternative were reviewed by the team, and the results were documented. The detailed results are included in this appendix for four of the 15 alternatives that were fully evaluated. Volume II, Appendix D provides the selection criteria assessments of all 15 alternatives.

C.2.1 Selection Criteria Assessment for Alternative Vitrification 1

Alternative Vitrification 1:

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. ***Residual threat to health and environment upon successful completion***

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents – all retained – amount increased by treatment.]

1.1.1.1. Nitrates/nitrites – Low residual toxicity. Nitrate/nitrite are nearly completely destroyed by vitrification and offgas processes – small residuals in caustic scrub solution that is sent to the Effluent Treatment Facility (ETF) and end up grouted for disposal in the Integrated Disposal Facility (IDF).

1.1.1.2. RCRA metals – High residual toxicity. RCRA metals are contained in the primary waste form except mercury. Final partitioning of mercury has high uncertainty. All primary offgas components will have mercury contamination and secondary offgas components will have mercury contamination up to the granular activated carbon (GAC). Mercury captured on the GAC will be micro-encapsulated in grout. Some mercury will partition to the Liquid Effluent Retention Facility (LERF)/ETF and end up in a grouted waste form disposed of in IDF. No destruction; mercury is vaporized to secondary stream.

1.1.1.3. Land Disposal Restrictions (LDR) organics – Low Residual toxicity. Most organics are destroyed by the vitrification and secondary offgas processes. Some organics generated by incomplete combustion of sugar would be captured in the submerged bed scrubber (SBS) condensate and partitioned to LERF/ETF for destruction. Some organics will be captured by the GAC and grouted for disposal in IDF. Organics in waste largely destroyed, whereas melter produces some; remaining organics partition to secondary waste and are destroyed or sequestered in subsequent treatment; if planned disposition is found inadequate, it is assumed that changes would be made to processes to be within regulatory requirements.

1.1.1.4. Ammonia – High residual toxicity. The vitrification process generates ammonia that will be partitioned to the LERF/ETF for treatment. In addition, ammonia is added to the secondary offgas system (to destroy NO_x) and emitted from the vitrification facility stack. Ammonia in ETF will be precipitated and incorporated into a grout waste form disposed of in IDF with unknown long-term behavior.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides
[MOE: Estimated peak groundwater concentration at IDF Performance Assessment (PA) compliance point over ~1,000 years (to DOE O 435.1, *Radioactive Waste Management*; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period) (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*).

1.1.2.1.1. Iodine – Iodine is expected to partition predominately to solid and liquid secondary wastes (liquid/solid/gas). Release rates for some macroencapsulated components (solid secondary waste, e.g., GAC) expected to be higher than microencapsulation of iodine in liquid secondary waste grout from ETF; both are disposed of in IDF (without getters) but improvements to primary waste form could be applied to secondary wastes.

1.1.2.1.2. Technetium (non-pertechnetate is evaluated in Section 1.2.2.2) – Most (~99%) ^{99}Tc assumed to be retained in the primary waste form – and 2017 IDF PA predicted low-activity waste (LAW) glass contribution to be 10× lower than compliance limit. A small fraction will be captured on the high-efficiency particulate air (HEPA) filters, which are crushed and macroencapsulated in grout. Leach rates from the spent HEPAs is evaluated in the current PA but predicted quantities of technetium on HEPA filters are assumed to be extremely low but do not accurately account for system full performance.

1.1.2.1.3. Selenium-79 (^{79}Se) – Uncertainty in partitioning due to volatility. Like ^{99}Tc, a small portion could be captured on the spent HEPA filters that are microencapsulated and disposed of in IDF. Low inventory of ^{79}Se (114 Ci, see Volume II, Section E.3.1.3) leads to minimal risk to drinking water.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites. N/A – Destroyed in melter with small amount of nitrate produced and present in the ETF liquid secondary waste, and IDF PA risk budget tool showed peak concentrations 10× below on drinking water standards.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives.] – Ammonia is generated by the melter process (when sugar used as a reductant) and is also added during secondary offgas treatment to destroy NO_x. Ammonia from the melter process is typically partitioned to LERF/ETF while excess ammonia added during secondary offgas treatment is exhausted from the vitrification facility stack. Ammonia will also be present from first LAW melter system so its presence at ETF is not differentiating among alternatives. Ammonia in ETF is precipitated and encapsulated in grout waste form disposed of in IDF. Release from waste form at some TBD rate either during production, curing, or disposal is likely.

1.1.2.4. RCRA metals – [MOE is leachate Toxicity Characteristic Leaching Procedure (TCLP) compliance.] Leach rates of RCRA metals from the glass are predicted to be very low and expected to pass TCLP.

1.1.2.4.1. Mercury – [MOE is retention of mercury in primary vs. secondary waste form.] Mercury will not be retained in glass and will end up in a grouted waste form for all options. For vitrification, the mercury will be portioned throughout the secondary wastes, with most presumed to be on the activated carbon bed.

1.1.2.4.2. Chromium – [MOE is retention of chromium in waste form.] Chromium will be captured in the primary waste form and leach rate dependent on the dissolution rate of the glass. Like technetium, a small fraction could be partitioned to the spent HEPA filters that are macroencapsulated in grout and disposed of in IDF.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals (e.g., lead) appear not to exceed Drinking Water Standards (DWS) limits and are significantly beneath concentration of chromium.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – For 1 gallon of LAW feed: 0.34 gallons of primary waste glass, 0.05 gallons of spent equipment, 0.05 of grouted solids from ETF, and 1.8 gallons of liquid effluent disposed of at a state-approved land disposal site (SALDS). (Note: Flush volumes not included in water effluent totals) (RPP-RPT-63328, *Calculating the Non-Monetary Impact of Operating a Vitrification Facility*).

1.2. Long-term risks upon successful completion
[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Destruction of organics. High uncertainty exists in the speciation of the organics in the waste feed; the amount and speciation of organics that will be vaporized, destroyed, or produced by the melter and scrubbed from the offgas in the primary offgas system and subsequently sent to LERF/ETF; and the amount and type of organics that will be captured on the GAC, which is microencapsulated and disposed of in IDF.

1.2.1.2. Nitrates/nitrites – High confidence that nitrate and nitrite will be nearly completely destroyed by the immobilization process.

1.2.1.3. Ammonia/ammonium ion – Moderate risk. None in primary waste form. Ammonia in secondary liquid waste treated at LERF/ETF and will be in the immobilized waste form disposed of in IDF.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – Moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – Moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with regard to groundwater

1.2.2.1. Iodine – Moderate confidence overall. Low confidence that partitioning of iodine through process will proceed as expected and what resulting speciation will be. High confidence that the amount of iodine in secondary wastes will be higher than assumed in IDF PA. Partitioning significantly impacted if melter idles frequently. Any iodine retained in glass will have low leach rates dependent on glass stability. Low confidence in the immobilization of iodine in either stabilized solid secondary waste (e.g., GAC) or stabilized liquid secondary wastes assuming no getter used in secondary waste grout. Iodine is a key constituent of interest in the IDF PA. ^{129}I can define waste classification but concentrations in secondary wastes are lower than the U.S. Nuclear Regulatory Commission (NRC) low-level waste (LLW) Class A limit[1]. Once released by chemical reactions and leached into the subsurface there is limited to no natural attenuation of iodide, and as such the secondary waste iodine inventory could impact groundwater compliance limits. Mitigated during the compliance period by low rate of water to transport.

1.2.2.2. Technetium (including non-pertechnetates) – Moderate confidence overall. High confidence that partitioning of technetium through process will proceed as expected, including non-pertechnetate (converts to pertechnetate in melter). (Note: It is also expected that the amount of ^{99}Tc in secondary wastes will be higher than assumed in IDF PA due to model simplifications that did not incorporate all known impacts on ^{99}Tc partitioning.) Partitioning to offgas is significantly impacted if melter idles frequently or wet electrostatic precipitator (WESP) deluge frequency/time is higher than expected or if its scrubbing efficiency is lower than expected. Any ^{99}Tc in the primary glass waste form will have leach rate dictated by stability of the glass. Within the grouted secondary waste form, there is high confidence that technetium will be reduced and insoluble technetium. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form can be destabilized with time due to oxidation but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA.

[1] ^{129}I is listed in Table 1 of 10 CFR 61.55 *Waste Classification*, that is used to classify wastes for near-surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

Technetium can define waste classification and concentrations may approach the Class A limit[2]. Once in the subsurface, there is limited to no natural attenuation of technetium, and as such the secondary waste grout technetium inventory could impact groundwater compliance limit.

1.2.2.3. ^{79}Se – High confidence in minimal risk. Limited to no data to date on the partitioning in Waste Treatment and Immobilization Plant (WTP) and mobility within grout waste forms. ^{79}Se is a RCRA metal (as selenium) but only a small inventory across the Hanford tanks (2 kg) may reach the secondary waste. Selenium has limited attenuation in the Hanford subsurface. The limited inventory may minimize overall risk to groundwater. Mitigated during the compliance period by minimal water infiltration thru vadose zone.

1.2.2.4. Nitrates/nitrites – High confidence that nitrate/nitrite will not impact groundwater due to destruction during process and added nitrate/nitrite had limited impact in the 2017 IDF PA from secondary wastes.

1.2.2.5. Ammonia/ammonium ion – Moderate confidence overall. Liquid secondary waste streams will contain significant ammonium that can be converted to ammonia in alkaline condition. Use of an ammonia tolerant grout can limit ammonia release in processes but long-term stability unknown. From the waste form, ammonia can both evaporate as vapor and leach to soil. Mitigated during the compliance period by low amount of water infiltration.

1.2.2.6. RCRA metals – High confidence that RCRA metals (except mercury) will be effectively immobilized in a primary waste form with low leach rates. Mercury is partitioned entirely to secondary waste streams.

1.2.2.6.1. Mercury low confidence in overall fate – Mercury to partition to GAC where it will be stabilized/macroencapsulated as solid secondary waste. High confidence in ability to pass TCLP using slag in grout formulation with a high confidence in ability to sequester due to mercury sulfide formation. High confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface. Expect to be absorbed primarily in sulfur-impregnated carbon bed; but will be widely distributed in the offgas system and some to LERF/ETF; mercury leaching from carbon bed has been tested but not elsewhere in the system.

1.2.2.6.2. Chromium – High confidence in expected retention in glass waste form, refractory, and bubblers with low leach rates from glass dictated by stability of the glass.

1.2.2.6.3. Other RCRA metals – High confidence that other RCRA metals are expected to be in glass waste form and expected to leach at rate dictated by the durability of the primary glass waste form.

[2] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

1.2.3. Confidence in total volume of primary and secondary waste forms produced
Overall moderate confidence. High confidence in volume reduction of primary waste form. Medium confidence in amount of secondary waste generated – if total operating efficiency (TOE) is lower than projected, it would lead to higher secondary waste volume per liter of feed, which would lead to larger amounts disposed of in IDF.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk.
[MOE is time to start and processing duration risk of tank leaks for both double-shell tanks (DST) and single-shell tanks (SST) is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.2 for more detail). Startup in ~25 years, 3-year ramp up to full processing rate, low flexibility in processing rate, moderate throughput/TOE, complex and unique components, high maintenance needs, and large secondary waste handling needs increases risk of delays and therefore increases risk of additional leaks. Startup of this process in ~25 years has high risk of additional tank leaks because retrievals would be delayed vs. the schedule to support high-level waste (HLW), increasing time available for corrosion-induced leaks due to ongoing tank degradation.

Continuity of operations after startup – loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Because this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative consumes the entire initial benchmark supplemental LAW treatment budget, providing no opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is no potential for reducing risk of leaks.

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety
[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Multiple hazards. The high temperature process results in volatilization of selected radionuclides, increasing the risk for worker exposure. In addition, the buildup of radionuclides (^{99}Tc, ^{137}Cs, ^{129}I, others) in the recycle flywheel between the melter, offgas, and evaporator systems increases the exposure risk. The size and scope of the operations increase the number of workers exposed during normal operations and the extensive use of consumables (e.g., bubblers, melters, HEPA filters, GAC) require frequent exposure of these workers to hands-on maintenance activities with potential direct exposure to the radioactive material. Construction would be near operating radioactive facilities and ground contamination (i.e., contamination risk due to high vapor concentration due to flywheel, secondary waste handling, and extensive maintenance).

2.2.1.2. Chemical exposure – Multiple hazards. Similar to radiation exposure, the high temperature process results in volatilization of selected chemical species of concern and the generation of toxic offgas, increasing the risk for worker exposure.

In addition, the buildup of species (e.g., mercury) in the recycle flywheel increases the exposure risk. The size and scope of the operations increase the number of workers exposed during normal operations and the extensive use of consumables (e.g., bubblers, melters, HEPA filters, GAC) require frequent exposure of these workers to hands-on maintenance activities with unavoidable direct exposure to the chemical species. Furthermore, the use of hazardous chemicals (e.g., NaOH, anhydrous ammonia) in the process add to the hazards faced by workers. (38 high hazard consequences [RPP-RPT-63328].)

2.2.1.3. Particulate exposure – Few hazards that are not easily mitigated. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates. Mitigated by common commercial practices.

2.2.1.4. Physical injury – Moderate hazards. The large number of maintenance and other activities required for the vitrification process increase the exposure of hands-on workers to industrial hazards. 38 high hazards conditions were noted by Washington River Protection Solutions, LLC (WRPS) for vitrification of LAW (due to large number of maintenance activities) (RPP-RPT-63328).

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments of rad/hazardous shipments to high number of rad/hazardous shipments.)] – Low risk. The vitrification alternative generates the lowest waste volume amongst alternatives, and it is expected that all waste is disposed of in the IDF leading to the lowest possible transportation risk. Transport of hazardous chemicals (NaOH, anhydrous ammonia) to the site represents an exposure risk due to accidents.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] (High discharge volumes; new ETF believed necessary.) – Water is not incorporated in the primary waste form and large volumes of water are added during the treatment process. The liquid effluents from the vitrification process require additional treatment prior to release, using the existing LERF/ETF or a new, similar facility. A large fraction of the ^{129}I from the waste feed is expected to be in the liquid secondary waste and could result in an additional waste stream if the ^{129}I must be removed prior to sending the effluent to LERF/ETF. Approximately 2-3 gallons of treated wastewater will be sent to SALDS for each gallon of supplemental LAW feed. Tritium is all released to the environment [SALDS] immediately.

2.3.2. Atmospheric discharges

[MOE: Fraction of radionuclides and contaminants of concern (CoC) converted to vapor in offgas system.] – Expect 34 MT NH_3 and 4 MT "other" per 1 Mgal feed; 0.006 mrem ^{14}C discharge (RPP-RPT-63328); potential for ^{129}I.

2.3.3. Transfer/process tank (on-site) spills
[Unplanned discharges MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category.)] (Low – only risk is transfers to LERF or Effluent Management Facility [EMF].) – The large number of unit operations and high temperature operations, the corrosive nature of the recycle stream generated, and the use of corrosive chemicals increase the chances for on-site spills during treatment compared to other options (but all transfer lines have secondary containment).

2.3.4. Off-site transportation spills
[MOE: No risk of off-site spills to high risk for off-site spills.] – Low risk. No shipments of liquid and no off-site immobilized waste. Off-site transportation risks include delivery of chemicals, including liquids such as sodium hydroxide and anhydrous ammonia, diesel fuel, and other industrial chemicals and glass-forming chemicals (GFC)/minerals.

2.3.5. Secondary waste streams generated
[MOE: Volume of waste (liquid and solids and equipment); low quantity of secondary waste to highest quantity of liquids, solids, and equipment.] – Very high volumes. Millions of gallons of liquid secondary waste are generated annually, leading to the requirement for additional treatment capacity at the LERF/ETF. In addition, the short operating life of components of the vitrification process (e.g., melters, bubblers) and the large number of consumables (e.g., HEPA filters, GAC media) lead to large volumes of solid secondary waste. The waste streams will likely contain significant portions of the ^{129}I, all the mercury, and some of each of the other CoCs in the waste feed. Spent melters are placed in containers and disposed of in IDF. Melters have an estimated operational lifetime of five years.

2.3.6. Greenhouse gas emissions (see Section 2.3.2 above) – At a minimum, treatment of 1.0E6 gallons of waste consumes 1,500,000 gallons (4,800 MT) of diesel fuel (~15,000 MT as CO_2), 168 MT sugar, 283 MT soda ash (sodium carbonate), 295 MT lithium carbonate (total of ~550 MT as CO_2), 74 GWh of electricity, and requires approximately 570 deliveries of fuel oil, glass formers, and other process chemicals (based on information from RPP-RPT-63328, and DOE/RL-2022-33, *Hanford Energy Emissions 2022-2037 – Reducing the Gap to Net Zero*[3]).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) – The existing WTP LAW Vitrification Facility required approximately 20 years to complete. A supplemental LAW vitrification facility is expected to be at least twice as large as the WTP LAW Vitrification Facility and should be expected to take at least as long to construct. However, some efficiencies in design and construction could occur since the design is expected to be similar to the existing WTP LAW Vitrification Facility. In the benchmark funding scenario, the cost of the vitrification facility would extend the required schedule and would likely preclude completion of the facility in the time required. Hot start-up (CD-4) in ~2050 (see Volume II, Appendix F).

2.4.2. Duration to full capacity (additional years) – The facility would need to ramp up to full production in a short period of time (6 months) to support HLW processing. However, startup of similar facilities indicate that is more probable that a supplemental LAW facility would require 3 years to ramp up to full operations.

[3] Fuel oil and deliveries amount adjusted for annual consumption in DOE/RL-2022-33 vs. 1M gal of waste in 154 days per RPP-RPT-63328.

2.4.3. Duration of operations (additional years) – The facility would operate until the end of the entire HLW campaign. HLW campaign will begin later because the supplemental LAW treatment starts later. Additional delay to supplemental LAW treatment startup extends duration that existing equipment and first LAW melters must operate, exacerbating maintenance needs and requiring replacement of equipment and facilities that exceed their design life.

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues – Moderate risk that technical issues could delay startup. Expect first LAW to inform supplemental LAW melter design and operation, along with lessons learned from the Defense Waste Processing Facility and West Valley melters and pilot testing at Catholic University of America. Uncertainty exists in radionuclide partitioning and behavior across all waste compositions, production of LDR organics, along with overall integrated system complexity and additional facilities needed (e.g., ETF). (Delays due to technical uncertainties contribute to increased cost risk and therefore the potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – Very high risk of delay. Complex system with high maintenance requirements, multiple melters with partially shared systems, long operating duration, high temperatures, extensive balance of facilities, can contribute to potential extension of supplemental LAW and HLW processing duration.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Tech failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste, i.e., failure mode likelihood and result – this should be customized for each alternative with each unique failure mode and consequence.) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] The vitrification alternative will use the same flowsheet and approach as the existing WTP LAW Vitrification Facility. Portions of the process have been extensively tested using pilot-scale systems, but selected unit operations have very limited or no testing (e.g., the GAC and caustic scrubber). Uncertainty remains in the partitioning of selected species, but the baseline process is considered robust and able to immobilize the waste sodium in a glass waste form.

3.1.1.1.1. Corrosion of offgas system causing frequent extensive repairs/replacement – Very low risk of failing to complete, despite high volatility and recycling of offgas condensate leads to rapid corrosion of offgas system components (where mercury has been absent from testing but not believed to cause dramatic impact; pilot-scale system could have differences). Consequence: Frequent shutdown and component replacement.

Mitigated by operation of the WTP LAW Vitrification Facility that will help guide material of construction for supplemental LAW treatment.

3.1.1.1.2. Fire in offgas system – Low risk of failure to complete, but there is potential for fire in carbon bed; supplemental LAW could have different offgas components (organics, NO_x) (where mercury has been absent from testing but not believed to be impactful; pilot-scale system could have differences). Monitoring of gases and temperature in GAC mitigates risk. Consequence: Extended duration shutdown; system redesign/rebuild. Extended delays. Mitigated by operation of the WTP LAW Vitrification Facility that would help guide process for supplemental LAW treatment.

3.1.1.1.3. Release of radioactive material (e.g., ^{129}I, ^{3}H) or mercury or NH_3 (above permit) to atmosphere – Risk is unexpected partitioning of species under melter and offgas system operating conditions but would be mitigated if release occurs, so very low risk of failure to complete (pilot-scale system could have differences). Consequence: extended duration shutdown, system redesign/rebuild. Extended delays. Mitigated by operation of the WTP LAW Vitrification Facility that would help guide design and operations for supplemental LAW treatment.

3.1.1.1.4. Ability to control WESP as it ages – Very low risk potential to make collection of technetium ineffective; risk is unexpected partitioning of species under melter and offgas system operating conditions (where pilot-scale system could have differences). Consequence: extended duration shutdown, system redesign/rebuild. Delays. Mitigated by operation of the WTP LAW Vitrification Facility that would help guide design and operations for supplemental LAW treatment; ability to wash technetium from HEPA filters or dispose of offsite.

3.1.1.1.5. Overall uncertainty of I partitioning – Iodine partitioning was tested, so low uncertainty remains, but problematic amounts could distribute to caustic scrubber solution bound for ETF. Consequence: excess partitioning to caustic scrubber requiring mitigation instead of sending to LERF/ETF. Mitigated by data from LAW melter operation.

3.1.1.2. Process complexity (flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Very high process complexity. Vitrification of the supplemental LAW feed requires a large number of integrated unit operations and incorporation of a significant and variable recycle stream into the feed process. The high temperature processing generates an offgas that both requires extensive treatment prior to release and worker protections to prevent exposure. The process contains many items that require routine hands-on maintenance or replacement. The large recycle and extensive treatment system represent an interdependent and complex system where not all interactions are well understood.

Note that if designed the same as the LAW melter system, a single unit operation failure in the system will shut down the melter (or multiple melters for the secondary offgas system or GFC preparation system). In addition, the short cycle times of many of the feed and condensate handling processes require rapid turnaround of sample analyses, expedited batching of GFC batches, and complicates handling of the large number of receipts needed to keep the GFC silos and other process chemical feed tanks filled unless the feed tanks for supplemental LAW treatment are sized using a different basis than the current WTP LAW Vitrification Facility (very high interconnectedness). Consequence: Challenging to run system, delayed processing, additional costs, missed milestones. Mitigated by LAW Vitrification Facility operation providing input to operation and design but very high operating cost per day.

3.1.1.2.1. Unit Operations (33 systems listed below)

- Feed preparation tasks
  - Receipt of feed and recycle
  - Melter feed preparation
  - GFC batching
  - GFC blending and transfer
  - Melter feed system
- Melter
  - Feed compositional controls (high complexity)
  - Bubbler system (moderate complexity)
  - Cooling water system for refractory panels
  - Cooling for electrodes
  - Air lifts for pouring
  - Power supplies and electrode (moderate complexity)
- Primary offgas
  - Film cooler
  - Submerged bed scrubber
  - Wet electrostatic precipitator or steam atomized scrubber (high complexity)
  - Condensate collection
- Secondary offgas
  - Heater
  - HEPA
  - Activated carbon bed (moderate complexity)
  - Heat exchanger
  - Heater
  - Thermal catalytic oxidizer
  - Selective catalytic reduction unit (moderate complexity)
  - Caustic scrubber (moderate complexity)
- Effluent Management
  - Melter offgas condensate receipt and pH adjustment
  - Evaporation (moderate complexity)
  - Evaporator condensate collection and transfer to LERF/ETF

  - Evaporator concentrate collection and return to feed preparation process
- Container handling line
  - Pour cave
  - Fill height verification and inert fill station
  - Lidding station
  - Container swabbing and decon station (moderate complexity)
  - Container load out station.

3.1.1.2.2. Accuracy of controls needed

- Sampling/measurements needed to control process – Very high complexity. Batch qualification is expected to give composition for GFCs, but the internal recycle of concentrated melter condensate must be factored into the process. Sampling of the batch feed on a campaign basis, samples of each batch of recycle concentrate, and confirmation of the melter feed blend is currently performed for WTP LAW Vitrification Facility operations. If the process is closely coupled with HLW operations, additional sampling will be needed to account for the feed variations from the HLW effluents. In addition, sampling of the primary offgas condensate prior to evaporation and of the EMF evaporator condensate is expected during campaign transitions and if upset conditions occur.

  Control of the melter feed process is more art than science as the amount of cold cap coverage must be inferred from secondary indications and the response of the system to changes can take several hours. The secondary indications included melter pool and plenum temperatures. Cold cap coverage is controlled using melter feed rates and melter bubbling rates.

  These parameters also impact the reactions that occur in the melter plenum space such as reactions of nitrate to nitrogen, nitrous and nitric oxides, and ammonia, and the amount of feed organic destruction and production of organics from sugar. Consequence: Delayed processing, complex interrelated systems, melter idling causing variability in recycle composition. Mitigated by experience with LAW melter operation.

- Modeling needed to control process – Very high complexity. The vitrification process is driven by compositional requirements to efficiently process in the plant and produce an acceptable glass with predictable properties. The glass composition models predict the glass viscosity, liquidus temperature, product consistency test (PCT) and vapor hydration test (VHT) response, solubility of key components (e.g., sulfur, chromium), and electrical conductivity. The model is also used to predict glass composition for reporting purposes. Uncertainty in sample analysis accuracy and models. Consequence: See items below. Mitigated by experience with LAW melter operation.
  - Failure modes for improper operation
    - Glass viscosity

    - Improper viscosity (low or high) can cause the pour stream to drip, leading to strands of solidified glass between the pour spout and container. The pour stream can be diverted by these strands and could miss the container. Pour cell cameras are installed to monitor the pouring operation.
- Improper composition
    - High sulfur – If excessive sulfate is fed to the melter (or insufficient sugar) a gall layer can form on the surface of the melter that could lead to early failure of the bubblers and/or melter.
    - High chromium – Could lead to formation of crystals in melter.
- Liquidus temperature
    - Crystal formation could be mild or severe depending on magnitude of error. A gross error leading to large amounts of crystal formation is not considered likely. A small amount of crystals from a minor error could likely be handled by the vitrification system, but it is possible for crystal formation to negatively impact the melt composition leading to changes in viscosity, conductivity, etc.
- Electrical Conductivity
    - As with liquidus temperature, large errors that would lead to major processing issues are not expected. Improper electrical conductivity would lead to issues with maintaining the melter at temperature.
- PCT and VHT
    - PCT and VHT responses are modeled with no feedback mechanism in place during processing if the models are inaccurate at predicting glass performance. It will not be known that the glass did not meet durability limits unless future testing indicates issues with the specific composition poured or excessive leach rates are noted from the disposal site. The likelihood of glass composition issues causing excessive leaching from the IDF is considered low.
- Container composition
    - The composition of the glass in the container uses a simple model for single-pass glass retention for each species in the feed to predict the composition of the poured glass. The model currently does not account for cold cap coverage, idling, or other processing conditions. Thus, the composition of semi-volatiles in the reported glass compositions is likely to have a high amount of uncertainty.

3.1.1.2.3. Commercially available/similar (of a type) to available/bespoke systems – High number of custom components. Portions of a supplemental LAW vitrification facility could use commercially available equipment (e.g., exhaust fans, mixers, pumps), most components are of similar type systems modified for the supplemental LAW treatment facility and some systems are complete bespoke (e.g., melters, film coolers). Consequence: need to redesign/rebuild, causing mission delays. Mitigation is to get business to make replacement; build in on-site shop; purchase extras.

3.1.1.2.4. Overall flowsheet integration complexity – The flowsheet for a vitrification facility for supplemental LAW is extremely complex. The recycle of offgas condensate to the front end creates variability in the feed, a large number of GFCs must be accurately added to achieve high waste loadings using complex models to determine the required amounts for each batch, the feed to the melter must be distributed across three zones, the cold cap coverage must be inferred from secondary indicators, and the offgas system consists of 12 separate unit operations. The condensate from the primary offgas system must be evaporated and recycled. Two separate liquid effluent streams are generated, along with several solid waste streams. Life expectancy of the melter bubblers is expected to be ~6 months, requiring frequent maintenance on the melters to be balanced with the operating schedule. Operating experience from WTP LAW Vitrification Facility will help with the supplemental LAW treatment facility design and operation. Consequence: Delayed processing, complex interrelated systems, melter idling causing variability in recycle composition. Mitigated by experience with LAW melter operation.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed) – Vitrification requires extensive utilities, including large demands for diesel fuel, cooling water, electricity, steam, and compressed air, and process chemicals such as anhydrous ammonia, sodium hydroxide, sugar, and 12 GFCs. Sample requirements necessitate an integrated analytical facility operating on a 24/7 schedule. Cross-site supernatant liquid transfer line is needed to support this alternative. Secondary waste generation and limited lag storage require treatment facilities for these streams to be available. Operating experience from WTP LAW Vitrification Facility will help with the supplemental LAW treatment facility design and operation. Consequence: Delayed processing, complex interrelated systems, melter idling causing variability in recycle composition. Mitigated by experience with LAW melter operation.

3.1.1.4. Required demolition/removal/modification
It is expected that siting will not require demolition or removal of existing facilities. No consequences.

3.1.1.5. Technology Maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – The vitrification alternative will use the same flowsheet and approach as the existing WTP LAW Vitrification Facility. Portions of the process have been extensively tested using pilot-scale systems. Uncertainty remains in the partitioning of selected species, but the baseline process is considered robust to be able to put the waste sodium into a glass waste form. WTP LAW processing of direct-feed low-activity waste (DFLAW) feed should reduce uncertainty in the partitioning of these species while the supplemental LAW treatment facility is built. Consequence: Delayed processing. Mitigated by experience with LAW melter operation.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – WTP LAW processing of DFLAW feed should reduce technical uncertainty while the supplemental LAW treatment facility is built. Consequence: Delayed processing. Mitigated by experience with LAW melter operation.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions
[High heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – The ability to adjust waste loading and GFC recipe will allow a supplemental LAW vitrification facility to handle a wide range of feeds. Predicted waste soda loading for LAW range from 3-4% up to 25% with most batches over 20%. Non-pertechnetate is not an issue for the vitrification process since any non-pertechnetate not retained by the glass will react to form pertechnetate in the melter offgas system. Consequence: Delayed processing. Mitigated by experience with LAW melter operation.

3.1.4. Ability to incorporate future advances
[MOE: Easily incorporated to impossible.] – The high capital cost and unique operations makes incorporation of future advances challenging. Consequence: high cost of changes.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW budget.] – The funding needs for a supplemental LAW vitrification facility will likely exceed the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – The peak funding needs for a supplemental LAW vitrification facility will likely greatly exceed the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – Vitrification facilities have limited ability to operate at lower rates than needed to maintain a cold-cap on the melter as operating with a small cold cap results in excessive losses of semi-volatiles to the offgas. Idling the melter at temperature to allow enough feed to accumulate to allow operation for a period of time with a full cold cap also results in high semi-volatile losses. A cold shut down requires the melter to be replaced. Given that multiple melters are required, it may be feasible to allow a portion of the melters to remain in extended idle during periods of reduced feed, but this option still uses significant resources and melter life is not extended by idling. The "SLAW feed vectors" have considerable variability in the amount to be treated each month. Sufficient lag storage to provide a constant feed to the supplemental LAW treatment facility is not feasible.

3.2.4. Expected work remaining at failure point

[MOE: failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; text to funding shortfall/timing; describe when it fails; MOE is consequence only.) – A supplemental LAW vitrification facility failure is assumed to be caused by lack of funding during construction. Consequence: Alternate technology/solution must be developed. Delayed mission, delayed start of supplemental LAW processing. It is unlikely that sufficient funds will be available to complete a vitrification facility by the project need date.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not complete and never starts up. Start of the supplemental LAW treatment mission is delayed. Worst case is to commit to vitrification option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is unlikely that sufficient funds will be available to complete a vitrification facility by the project need date.

3.3. Likelihood and consequences of failing to complete due to unavailability of key services and materials

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider)] – The refractory used for the melters and other components have a single U.S. vendor. One system, the carbon dioxide decontamination system, has already been removed as a result of the vendor going out of business (along with previously unresolved issues with asphyxiation hazards).

Analytical services for WTP are provided by an on-site laboratory; this laboratory may not be able to handle the sample load from supplemental LAW vitrification facility with multiple melters, depending on configuration and sample requirements. Consequence is switching to an available material/equipment, expand capability, etc.; potentially causing additional cost and delays. While some delays may occur, a supplemental LAW vitrification facility is sufficiently large that it is not likely that a provider would be unwilling to provide materials or specially engineered parts.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above (all costs are discounted at 3% rate).

Total: $12,700 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$7,608 M (includes commissioning costs)

Note – Evaporation assumed provided by mission as part of HLW feed preparation facility.

4.2. Operations costs

$5,092 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

C.2.2 Selection Criteria Assessment for Alternative FBSR 1A

Alternative FBSR 1A: Fluidized Bed Steam Reforming On-site (A) Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents – all retained – amount increased by treatment.]

1.1.1.1. Nitrates/nitrites – Low residual toxicity. Nitrate/nitrite are destroyed by fluidized bed steam reforming (FBSR) and in the offgas system, and are essentially nondetectable in the primary waste form, but the offgas still contains some NO_x gas species. Nitrates were destroyed to detection limit levels (0.002 wt%) in the mineralized product, and overall offgas NO_x destruction was measured at between 91-94%, exceeding the goal for the Hanford LAW and WTP secondary waste simulants tests. (RT-21-002, *Report for Treating Hanford LAW and WTP SW Simulants: Pilot Plant Mineralizing Flowsheet*). Trace amounts of nitrate in the primary waste form would be insignificant in the disposal environment.

1.1.1.2. RCRA metals – High residual toxicity. RCRA metals are contained in the primary waste form except for mercury. All mercury is presumed to evolve to the offgas. All primary offgas components will have mercury contamination and secondary offgas components will have mercury contamination up to the GAC. Mercury captured on the sulfur-impregnated GAC would be micro-encapsulated in grout. No destruction.

1.1.1.3. LDR organics – Low residual toxicity. Most organics are destroyed by the FBSR and secondary offgas process. Some organics may be generated by incomplete combustion of coal but would be destroyed in the thermal oxidizer (TO). Organics in waste largely destroyed to non-detectable levels in the primary waste form, remaining organics destroyed in offgas system to within regulatory limits. Leftover coal in primary waste form, but not believed to be an issue.

1.1.1.4. Ammonia – Very low residual toxicity. The FBSR process should destroy whatever ammonia is in the LAW and does not introduce ammonia into the system. Ammonia and related compounds are likely produced in the denitration and mineralizing reformer (DMR) but are expected to be destroyed in the TO. No ammonia for long term impact.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Selected findings from the ASTM C1285, *Standard Test Methods for Determining Chemical Durability of Nuclear, Hazardous, and Mixed Waste Glasses and Multiphase Glass Ceramics: The Product Consistency Test (PCT)*, short-term and long-term durability testing, single pass flow-through (SPFT) testing, and pressure unsaturated flow-through (PUF) testing of the FBSR granular waste form produced from bench-scale, pilot-scale and engineering-scale testing indicate that (1) ASTM C1285 (PCT) releases would be expected to be near or more likely well below 2 g/m^2 (target), which means short-term, static release is comparable to processable WTP glasses,[1] (2) SPFT test data for silicon from the Savannah River National Laboratory (SRNL) bench-scale reformer (BSR) with modified radioactive tank waste product are two orders of magnitude lower than the data for LAWA44 glass, and (3) PUF test data indicates that rhenium release (analog for technetium) from a multiphase FBSR sodium aluminosilicate granular product is an order of magnitude lower than ^{99}Tc release from LAW glass (LAW AN102) (SRNL-STI-2011-00387, *Fluidized Bed Steam Reformed Mineral Waste Form Performance Testing to Support Hanford Supplemental Low Activity Waste Immobilization Technology Selection*; SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reser*vation). Thus, the normalized dissolution rates of the FBSR granular product are within the ranges of normalized dissolution rates for borosilicate glasses with compositions within the processable compositions of Hanford's WTP (PNNL-14805, *Waste Form Release Data Package for the 2005 Integrated Disposal Facility Performance Assessment*; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063, *Chemical Composition and PCT Data for the Initial Set of Hanford Enhanced Waste Loading Glasses*; PNNL-28838, *Enhanced Hanford Low-Activity Waste Glass Property Data Development: Phase 2*).

1.1.2.1.1. Iodine (Iodine mobility to groundwater is limited during the first 1,000 years compliance period due to facility performance) – Iodine is expected to partition predominately to the granular product (SRNL-STI-2011-00387). Release rates for iodine are expected to be near or more likely well below the 2 g/m^2 target (ASTM C1285 [PCT]) for the FBSR granular product and monoliths (SRNL-STI-2011-00387).[1]

[1] Accounting for the surface roughness of the mineral granules indicates that the FBSR product leach rate would likely be two orders of magnitude lower than the 2 g/m^2 target and, when the surface roughness of the mineral granules is ignored, that the FBSR product has an equivalent leach rate to "vitreous waste forms" (SRNL-STI-2011-00387).

However, PCT alone on a pristine waste form is not necessarily indicative of long-term disposal (i.e., IDF) performance (e.g., without additional information on alteration phases, thermodynamic and rate law parameters, structural incorporation).

The previous comparative performance estimates based on PCT, SPFT, and PUF results for a single-vendor steam-reforming material (RPP-17675, *Risk Assessment Supporting the Decision on the Initial Selection of Supplemental ILAW Technologies*) that suggested "*[g]iven the uncertainties, the groundwater impacts [and thus the normalized dissolution rates] of SR [steam reforming] are comparable to those of WTP glass*" are uncertain (including structural incorporation of ^{99}Tc and ^{129}I inferred from leaching results and how thermodynamic and rate model parameters were estimated without uncertainty quantification) and can be considered optimistic estimates.[2]

To date, only rhenium has been shown to exist in sodalite cage resulting from steam reforming of Hanford LAW (Dickson et al., 2014; Mattigod et al., 2006; Dickson et al., 2015; Pierce et al., 2014). Rhenium can be a suitable surrogate for technetium, and it was inferred that technetium could also be incorporated into the sodalite cage of the FBSR product. No observation of iodine incorporation into the sodalite cage from the FBSR process has been made to date. Corrosion testing of FBSR granular products has shown apparent congruent releases of iodine and technetium/rhenium providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016). Furthermore, there is direct evidence of iodine incorporation into sodalite cages in studies focused on vapor-phase capture of iodine using sodalite materials (Maddrell et al., 2014; Sava et al., 2011), which suggests that iodine may also be structurally incorporated in the steam reforming granular product sodalite phase. Some iodine may be sorbed onto the GAC, quantity is uncertain.

[2] In RPP-17675, all ^{99}Tc was assumed to be in the nosean phase and other contaminants (including ^{129}I) were assumed to be released in proportion to the rate at which ^{99}Tc was released from the nosean phase. The sodalite phase (which is isostructural with nosean and considered the host phase for ^{99}Tc and ^{129}I in more recent steam reforming studies (SRNL-STI-2011-00387) was not considered in the Preliminary Risk Assessment. These inferences are further complicated by the possible solid solution with sodalite and nosean as end members that may be present in the granular product (SRNL-STI-2011-00387). Additional testing suggests that dilute, steady-state dissolution rates are consistent with earlier data; however, there remain questions to be resolved, including (1) the applicability of Transition State Theory to the multimineral phase granular steam reforming product and corresponding model uncertainty; (2) the estimation and uncertainty quantification of thermodynamic and rate model parameters (e.g., activation energy, log K) other than the intrinsic rate needed for long-term performance prediction, especially for any solid solutions formed; (3) the locations of ^{99}Tc and ^{129}I based on solid phase measurements to confirm the hypotheses (i.e., structural incorporation in the sodalite cage) inferred from leaching results; (4) the rate of re-oxidation of the granular product during disposal (allowing release of ^{99}Tc not in the sodalite cage); etc.

1.1.2.1.2. Technetium (Non-pertechnetate was evaluated in Section 1.2.2.2; technetium mobility to groundwater is limited during the first 1,000 years [compliance period] due to facility performance) – Most (~99%) ^{99}Tc will be retained in the primary granular waste form, which exhibits very low leach rates either from structural incorporation in sodalite or the reduced nature of the granular product (SRNL-STI-2011-00387).[3] The release rates would likely be within those for borosilicate glasses with compositions within the processable compositions of Hanford's WTP (PNNL-14805; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063; PNNL-28838), but dependent on partitioning, structural incorporation,[2] and reoxidation of the waste form during disposal. To date, only rhenium has been shown to exist in the sodalite cage resulting from steam reforming of Hanford LAW (Dickson et al., 2014; Mattigod et al., 2006; Dickson et al., 2015). Rhenium can be a suitable surrogate for technetium, and it was inferred that technetium could also be incorporated into the sodalite cage of the FBSR product. Corrosion testing of FBSR granular products has shown apparent congruent releases of iodine and technetium/rhenium, providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016). A small fraction will be captured on the HEPA filters, which are crushed and macroencapsulated in grout. Leach rates from the spent HEPA filters are evaluated in the current PA, but the inventory to be disposed of is TBD. Expect about same amount on HEPA filters as in vitrification. Better single-pass retention of technetium in primary waste form vs. vitrification, leading to less technetium in offgas/HEPA filters.

1.1.2.1.3. Selenium-79 (^{79}Se) – Assumed to partition like sulfur, with most ending up in the primary waste form with very low leach rates. Like ^{99}Tc, a small portion could be captured on the spent HEPA filters that are macroencapsulated and disposed of in IDF. Expect about same amount on HEPA filters as in vitrification. Minimal impact due to limited quantity; 114 Ci total in the Hanford tank farms (per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*, see Volume II, Section E.3.1.3). Assuming high mobility from waste form release to subsurface is many orders of magnitude below conservative DWS.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

[3] X-ray absorption spectroscopy (XAS) data on technetium indicates that the +7 oxidation state in the sodalite cage is between 65-79% in the reduction-oxidation (REDOX) range of the FBSR operation with remainder as +4 in TcO_2 oxide and/or $Tc_2S(S_3)_2$. During durability testing, including long-term testing, there was no change in durability with sample REDOX, indicating that the +7 fraction of the technetium is insoluble in the sodalite cage, while the +4 fraction of the technetium is insoluble in the oxide and/or sulfide form (SRNL-STI-2011-00387).

1.1.2.2. Nitrates/nitrites [MOE: Estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – N/A, destroyed in DMR.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives.] – Ammonia in tank waste is destroyed in the FBSR process. DMR may produce ammonia but will be destroyed in the TO and not present in solid waste form.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Leach rates of RCRA metals from the granular waste are expected to be very low either from the nature of the granular product or low inventory in the LAW feed (SRNL-STI-2011-00387).[4] Only exceedances of TCLP Universal Treatment Standards (UTS) limits to date were for elements intentionally spiked above realistic limits.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Mercury will not be retained in granular product and will end up in the activated carbon waste form, which is assumed to be encapsulated in grout. Expect geopolymer waste form and encapsulated GAC grout to pass TCLP.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form.] – Chromium will be captured in the primary waste form with very low TCLP leach rates, although additional iron oxide catalyst (IOC) may be required where this material is also used as a denitration aid in the FBSR process (SRNL-STI-2011-00387). Like technetium, a small fraction could be partitioned to the spent HEPA filters that are macroencapsulated in grout and disposed of in IDF. Expect geopolymer waste form to also pass TCLP.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals is not known but expected to pass TCLP (SRNL-STI-2011-00387). Some TCLP leaching values for antimony and cadmium exceeded UTS limits; however, these values were shimmed in the feed (without regard for TCLP) to allow quantitative evaluation of mass balance/offgas results. High confidence in small inventory of cadmium (where inventory is not recorded in the Best Basis Inventory [BBI] [2018]) because only small quantities of these chemicals are present in the waste and analytical data are limited (HNF-SD-WM-TI-740, *Standard Inventories of Chemicals and Radionuclides in Hanford Site Tank Wastes*). Only ^{125}Sb is recorded in the BBI because only small quantities of the other antimony isotopes are likely present in the waste. The total activity of ^{125}Sb (~615 Ci) as of 2018 translated to less than 0.5 gram in all Hanford tank wastes.

[4] TCLP analyses for most of the RCRA metals were well below corresponding UTS (40 CFR 268.48, "Universal Treatment Standards," Non-wastewater) (SRNL-STI-2011-00387). However, some TCLP analyses for antimony, cadmium, and chromium exceeded UTS limits depending on the laboratory performing the analyses. After additional evaluation (including inventory considerations for cadmium and antimony), only the chromium analyses for the simulant exceeded the UTS; however, the granular product made using radioactive waste passed TCLP for all RCRA metals including chromium. The IOC, added to enhance denitration, could potentially be used as a co-reactant to sequester chromium as $FeCr_2O_4$ (SRNL-STI-2011-00387).

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – For 1 gallon of LAW feed: 1.0 gallon of primary waste form, 0.018 gallons of spent equipment, HEPA filters, spent carbon sorbent, etc., and no grouted solids (from ETF) (RPP-RPT-63580, *Calculating the Non-Monetary Impact of Operating a Fluidized Bed Steam Reforming Facility*, and SRNL-STI-2011-00387).

1.2. Long-term risks upon successful completion
Exogenous risks (earthquake, catastrophic flood, volcano, etc.) are assessed as indistinguishable across all technologies and disposal locations.
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics/destruction of organics – Presumably, all of the organics in the waste would be destroyed in the DMR or in the TO.

1.2.1.2. Nitrates/nitrites – High confidence that nitrate and nitrite will be nearly completely destroyed by the immobilization process. Testing done on varying conditions for over 20 years confirms thermodynamics of nitrated compounds – they thermally decompose at temperatures <400°C (i.e., well below 725-750°C in the DMR) and are destroyed to at or below detection limits in the mineralized product.

1.2.1.3. Ammonia/ammonium ion – None in primary waste form. No ammonia is added to the process. Ammonium compounds like ammonium nitrate and ammonium hydroxide are thermodynamically unstable or boil at temperatures above about 200°C, well below the 725-750°C temperature of the DMR. Ammonia and ammonium compounds are efficiently destroyed at temperatures typically between 850-950°C in the TO, which is designed to efficiently destroy thermally stable compounds such as hydrogen cyanide and benzene. But limited testing done on varying conditions and effectiveness of offgas system.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state. Expect essentially all mercury to sorb onto GAC based on pilot-scale testing but mercury retains its toxicity.

1.2.1.4.2. Chromium – High confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity in the Hanford environment.

1.2.2. Confidence in immobilization with regard to groundwater

1.2.2.1. Iodine – High-moderate confidence that partitioning of iodine through process will proceed as expected (i.e., iodine will primarily end up in the granular product). Single-pass capture is high and minimal amounts in secondary waste form (GAC).

Low leachability expected in waste form where leaching tests (e.g., PCT, SPFT) suggest normalized dissolution rates of the FBSR granular product are within the ranges of normalized dissolution rates for borosilicate glass with compositions within the processable compositions of Hanford's WTP (PNNL-14805; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063; PNNL-28838).[5] However, structural incorporation of iodine in the sodalite cage structure (as inferred from leaching results [SRNL-STI-2011-00387]) is uncertain – and thus is the long-term performance of the waste form for iodine during disposal – because no solid phase measurements (for iodine) have been performed to confirm the structural incorporation hypothesis. However, there is direct evidence of iodine incorporation into sodalite cages in studies focused on vapor-phase capture of iodine using sodalite materials (Maddrell et al., 2014; Sava et al., 2011), which suggests that iodine may also be structurally incorporated in the steam reforming granular product sodalite phase. Corrosion testing of FBSR granular products has also shown apparent congruent releases of iodine and technetium/rhenium, providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016) (see Section 1.1.2.1.1).

1.2.2.2. Technetium (including non-pertechnetates) – High confidence that nearly all technetium is captured in primary waste form; remainder (minimal) is captured in HEPA filters. Non-pertechnetate would be expected to decompose in DMR and behave similar to pertechnetate from waste. Low leachability in waste form. Structural incorporation of technetium in the sodalite cage structure (as inferred from leaching results [SRNL-STI-2011-00387]) is uncertain – and thus also is the long-term performance of the waste form for technetium – because no solid phase measurements (for technetium) have been performed. To date, only rhenium has been shown to exist in the sodalite cage resulting from steam reforming of Hanford LAW (Dickson et al., 2014; Mattigod et al., 2006; Dickson et al., 2015; Pierce et al., 2014). Rhenium can be a suitable surrogate for technetium, and it was inferred that technetium could also be incorporated into the sodalite cage of the FBSR product. Corrosion testing of FBSR granular products has shown apparent congruent releases of iodine and technetium/rhenium providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016). Furthermore, the fraction of technetium that would not be structurally incorporated in the sodalite cage would be insoluble in the oxide and/or sulfide form (SRNL-STI-2011-00387). Thus, the release of technetium not structurally incorporated in sodalite would be expected to be low as long as the waste form remains reduced (i.e., is not reoxidized) (see Section 1.1.2.1.2).

1.2.2.3. ^{79}Se – Medium confidence that selenium will behave similarly to sulfur and be incorporated into primary waste form with low leach rates. Spiked non-radioactive selenium found to pass RCRA limits by TCLP testing, indicating retention in the waste form (SRNL-STI-2011-00387). Chemistry is expected to mimic sulfur. High confidence in small inventory, 144 Ci total (per RPP-ENV-58562).

[5] Release rates are expected to be near or more likely well below the 2 g/m^2 target (ASTM C1285 [PCT]) for the FBSR granular product and monoliths (SRNL-STI-2011-00387) (see Section 1.1.2.1.1).

1.2.2.4. Nitrates/nitrites – High confidence that nitrate/nitrite will not impact groundwater due to destruction during process.

1.2.2.5. Ammonia/ammonium ion – Destroyed in TO. None in primary or secondary (GAC/HEPA filter) waste form.

1.2.2.6. RCRA metals – High confidence that most RCRA metals with sufficient inventory (except mercury) would be effectively immobilized in primary waste form with low TCLP leach rates. Mercury is partitioned entirely to secondary waste streams (GAC).

1.2.2.6.1. Mercury – Expect to be absorbed primarily in sulfur-impregnated carbon bed.

1.2.2.6.2. Chromium – Expect to be retained well in reduced granular primary waste form initially (that may also require additional IOC where this material is also used as a denitration aid in the FBSR process [SRNL-STI-2011-00387]), but no long-term testing on granular or monolith reoxidation has been performed.

1.2.2.6.3. Other RCRA metals – Other RCRA metals expected to be in granular primary waste form and not expected to be leachable via TCLP. TCLP leaching values for antimony and cadmium exceeded UTS limits; however, these values were shimmed in the feed (without regard for TCLP) to allow quantitative evaluation of mass balance/offgas results. High confidence in small inventory of cadmium (not recorded inventory in BBI because only small quantities of these chemicals are present in the waste and analytical data are limited [HNF-SD-WM-TI-740]). Only ^{125}Sb is recorded in the BBI because only small quantities of the other antimony isotopes are likely present in the waste. The total activity of ^{125}Sb (~615 Ci) as of 2018 translated to less than 0.5 gram in all Hanford tank wastes.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – High-moderate confidence in volume reduction of primary waste form. Moderate confidence in amount of secondary waste generated.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage (see tank leak discussion in Volume I, Section 1.3.3 for more detail).] – High risk. Startup in ~15 years and 3-year ramp up to full processing rate, moderate flexibility in processing rate, undemonstrated throughput/TOE, complex and unique components, and potentially high maintenance needs contribute to high risk of delays and therefore increases risk of additional leaks.

Startup of this process in ~15 years has increased risk of additional tank leaks since retrievals would be delayed vs. the schedule to support HLW, increasing time available for corrosion-induced leaks due to ongoing tank degradation.

Continuity of operations after startup – Loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative consumes the entire initial benchmark supplemental LAW treatment budget, providing no opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is no potential for reducing risk of leaks.

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Multiple hazards. The thermal process produces a granular and potentially dusty waste form, which contains radionuclides, increasing the risk for worker exposure if exposed to product dust. The size and scope of the operations increase the potential for worker exposure during normal operations. The presence of product dust in the process also increases the potential for worker exposure during maintenance. Engineered and administrative controls would be required to prevent worker exposure. Construction would be near operating radioactive facilities and ground contamination. Low volatility of rads but potential for radioactive dust (e.g., maintenance activities on offgas equipment or containers of granular product).

2.2.1.2. Chemical exposure – Multiple hazards. Various chemicals and feed materials are used in the FBSR process. Besides the supplemental LAW feed itself, the process feed streams include liquid nitrogen and oxygen, clay powder, coal, fuel oil, activated carbon, sodium hydroxide, and sodium silicate solution. Alumina is a required startup bed material. The process also produces gases (e.g., CO, NO, and NO_2) that are irritants or toxic above certain concentrations. While these gases are efficiently destroyed in the process, they can exist in any gas leaks in worker spaces and would result in toxic, irritating, or O_2-deficient conditions. Dusts produced in the process can also include irritants or toxic chemicals. The size and scope of the operations increase the potential for worker exposure to gaseous or particulate chemical hazards during normal operation or maintenance. These hazards require mitigation through engineered and administrative controls.

2.2.1.3. Particulate exposure – Multiple hazards. Dry process feed streams (clay, coal, activated carbon), alumina in the startup bed, and the dry product waste form (prior to forming a monolith) contain dusts that require engineered and administrative controls to prevent exposure to workers during operations and maintenance. Product is granular with potential dust from the process gas filters (PGF). Radioactive dust is contained within process equipment.

2.2.1.4. Physical injury – The FBSR process includes various potential physical hazards, including mechanical, high temperature, cryogenic O_2 and N_2, dust, and low-O_2 hazards, all of which require mitigation during construction, operation and maintenance. 34 high hazards conditions were noted by WRPS for FBSR treatment of LAW (RPP-RPT-63580). Engineered controls mitigate hazards; construction/design will mitigate.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad.] [MOE: Few trip/shipments of rad/hazardous shipments to high number of rad/hazardous shipments.] – Moderate risk. The FBSR alternative that disposes primary waste form in IDF generates the mid-range waste volume and all waste is expected to be disposed of in the IDF leading to low transportation risk. Granular waste volume is ~1× the liquid waste volume (bounding value of 1.2× used for calculations).

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Low risk. Water is not incorporated in the primary waste form. Water is added during the treatment process for steam production and temperature quenching. This water is all evaporated and exits the stack; no liquid secondary wastes are produced. For the geopolymer monolith primary waste form option, water is added that becomes part of the solid monolith waste form. (Tritium is all released to the environment [stack] immediately.) Minimal liquid to ETF (no process liquids, only other types of liquid wastes such as potential decon solutions).

2.3.2. Atmospheric discharges

[MOE: Fraction of radionuclides and CoCs converted to vapor in offgas system.] – Atmospheric radionuclide and CoC discharges will be within regulatory limits and are not expected to be a discriminator. Oxidation of organic CoCs, mercury capture, $^{129}I/^{99}Tc/^{14}C$ capture, destruction of nitrates and NO_x, gas scrubbing, and filtration for both vitrification and FBSR are expected to achieve regulatorily compliant results for air emissions.

2.3.3. Transfer/process tank (on-site) spills

[Unplanned discharges MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Minimal risk of on-site spills (all transfer lines have secondary containment). No liquids are discharged from facility.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – No shipments of liquid and no off-site immobilized waste in the case of disposal at IDF. Off-site transportation risks include delivery of chemicals, including liquids such as sodium hydroxide, coal, clay, alumina, liquid oxygen, liquid nitrogen, and other industrial chemicals.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment); low quantity of secondary waste to highest quantity of liquids, solids, and equipment.] – No secondary liquid wastes are generated. Moderate amount of debris (spent GAC and HEPA filters comparable to vitrification).

2.3.6. Greenhouse gas emissions (see Section 2.3.2 above) – At a minimum, treatment of 1 Mgal of waste consumes 984 MT of coal (~3,200 MT CO_2), 200,000 gal fuel oil or natural gas (~2,100 MT CO_2), 19 GWh of electricity, and requires nearly 416 deliveries of clay, coal, and process chemicals (based on data from RPP-RPT-63580).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) – ~15 years.

2.4.2. Duration to full capacity (additional years) – The Integrated Waste Treatment Unit (IWTU) at Idaho National Laboratory (INL) has required about 9 years (up to now) to start radioactive feed after initial plant startup, which was mainly due to lack of technology maturation and several issues identified during IWTU plant startup that were neither identified nor resolved during preconstruction pilot/demonstration testing. With those IWTU lessons learned, time was included in the FBSR schedule estimate in the National Defense Authorization Act for Fiscal Year 2017 (NDAA17) study to provide for more extensive pilot/demonstration testing prior to supplemental LAW FBSR plant construction.

Considering IWTU plant startup experience, prior mineralizing FBSR demonstrations, and future pilot-scale FBSR demonstrations that would be performed as part of a project if selected for Hanford supplemental LAW treatment, time to full capacity for FBSR should be similar to vitrification, ~3 years.

2.4.3. Duration of operations (additional years) – The facility would operate until the end of the entire HLW campaign. HLW campaign will extend duration because the supplemental LAW processing starts later. Additional delay to supplemental LAW treatment startup extends the duration that existing equipment and WTP LAW melters must operate, exacerbating maintenance needs and requiring replacement of equipment and facilities that exceed their design life.

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues – High risk. Technology has not been demonstrated at scale with waste representing expected variability and uncertainty to produce a mineralized waste form in an integrated system. Feed system and offgas system are complex. Limited knowledge of waste form performance (i.e., lack of solid phase characterization to support structural incorporation inferences from leaching data, lack of thermodynamic and rate law data, and uncertainty quantification needed to predict long-term performance). (Delays due to technical uncertainties contribute to increased cost risk and therefore potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – High risk of delay. The FBSR is a complex system that includes many integrated subsystems that must all work together, or operations and maintenance costs may increase and exceed the annual budget.

3. Likelihood of successful mission

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk – Risks of things that would stop the project before completion (i.e., failure – which could be because the solution is cost/schedule prohibitive).

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste [i.e., failure mode likelihood and result] – this should be customized for each alternative with each unique failure mode and consequence)
[MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The FBSR alternative will use a similar feed flowsheet and approach as the existing WTP LAW Vitrification Facility, although the Hanford LAW FBSR uses a TO instead of a carbon reduction reformer (CRR), which was used at IWTU and found to be troublesome during startup. Portions of the steam reforming process have been extensively tested using pilot-scale systems, but for other applications (e.g., IWTU producing a carbonate waste form) and waste streams (e.g., sodium bearing waste at INL). Uncertainty remains in the partitioning of selected species (between product and offgas) and structural incorporation of ^{99}Tc and ^{129}I in sodalite (as inferred from leaching results and other circumstantial lines of evidence, as described in Section 1.1.2.1.1 and 1.1.2.1.2), but the baseline process is considered of moderate maturity to be able to put the waste sodium into a granular waste form. IWTU lessons will be incorporated, but with different flowsheet and waste form; consequence is that technology would be challenging. If a failure was imminent, it would likely be identified during pilot-scale testing.

3.1.1.1.1. Corrosion of offgas system causing frequent extensive repairs/ replacement – (Limited testing. Moderate temperatures. Halides are captured in DMR and do not vaporize appreciably.) The commercial Erwin ResinSolutions Facility FBSR system (formerly Studsvik Processing Facility) in Erwin, Tennessee has operated since the 1990s, using similar mineralizing product chemistry (Mason et al., 1999). However, corrosion of the PGFs has been a cause of delay for the IWTU. This issue has been addressed with more pilot/demonstration testing and new filters (ceramic instead of Inconel, which corroded and caused plugging) have been installed in IWTU, and are now undergoing additional testing. Other potential corrosion issues include potential corrosion of offgas system piping, etc. during long-term operation, to be determined during IWTU operation. Corrosion is mitigated through process control and monitoring and avoided when operation is maintained within established operating limits. Consequence: Potential for frequent shutdown and component replacement, delaying the mission completion and high costs. Mitigated by operation of IWTU and pilot-scale testing that will help guide material of construction; moderately easy to shut down and restart).

3.1.1.1.2. Fire in offgas system – Low potential for fire in carbon bed or PGF. Potential for fire in the PGF is prevented by consumption of oxygen in the DMR, and subsequent minimal concentration of oxygen (close to 0 vol%) in the PGF. Supplemental LAW treatment is expected to contain organics and nitrates, which if not efficiently destroyed in the DMR and TO, could encourage oxidation of GAC particles and even fire in the carbon bed.

GAC is downstream of the oxidizer unit, which (together with the DMR) efficiently destroys organics. But some NO_x gas remains, along with about 3-5% O_2, in the oxidizer outlet gas. Potential for a fire in the carbon bed is mitigated through process control and monitoring of the gas composition and avoided when operation is maintained within established operating limits during normal FBSR operation. Consequence: CoC release to the environment, extended duration shutdown, system redesign/rebuild, delaying mission and additional costs.

3.1.1.1.3. Release of radioactive material (e.g., ^{129}I, ^{3}H) or other CoCs (e.g., mercury, NO_x) (above permit) to atmosphere (technetium/iodine radionuclides are not vaporized as much as with vitrification) – Risk is unexpected partitioning of species under DMR/PGF and offgas system processing due to operating conditions, or failure of offgas system components (TO, filters) to adequately destroy or capture CoCs. Consequence: Restore operating conditions back to within established operating limits (which are fast to accomplish) or, in the event of equipment failure, extended duration shut down, system redesign/rebuild, delaying mission and additional costs.

3.1.1.1.4. Ability to control offgas system as it ages (mitigate by replacing components on a schedule) – Low risk of unexpected partitioning of species under DMR/PGF and offgas system operating conditions. Consequence: Challenging operations, requiring periodic replacement of offgas system components (e.g., TO components, filters, or activated carbon) on planned or accelerated schedule without significant mission delay; or in the case of equipment failure, extended duration shut down, system redesign/rebuild.

3.1.1.1.5. Overall uncertainty of iodine partitioning – Low uncertainty. Liquid waste variability and rapid reactions could impact consistent partitioning (i.e., how much ends up in the offgas system) of the iodine. Consequence: Excess partitioning to offgas system requiring mitigation. Mitigated by adding/modifying components in the offgas system; determine need for required unit operations during pilot-scale testing.

3.1.1.1.6. Waste form leachability is higher than allowable – Radionuclide and hazardous metal retention based on the crystalline (sodalite/nosean) structure of the granular product and ability to consistently incorporate CoCs (especially iodine and technetium) in the sodalite cage structure and reducing chemistry in the granular product for technetium (SRNL-STI-2011-00387). Work has been done to demonstrate treatment effectiveness for selected Hanford LAW compositions (i.e., although not from designed studies) that do not adequately represent the variability and uncertainty in the Hanford LAW feeds that would likely need to be treated. This lack of representativeness translates to the consistency of the granular waste form produced from treating the high salt solution (with variabilities and uncertainties outside the tested ranges) in FBSR.

The hypothesis of structural incorporation of important radionuclides (^{129}I and ^{99}Tc) inferred from leaching results and supported by circumstantial lines of evidence (see Sections 1.1.2.1.1 and 1.1.2.1.2) and metal retention due to the reducing granular product require additional (designed) testing, but presumably these issues could be resolved prior to construction and startup. Consequence: High consequences that waste form leaches radionuclides or metals and cannot be disposed of without additional processing. (Mitigation method for off-specification material could include placing the product in a high integrity container (HIC), or off-site disposal in an acceptable commercial disposal site. Mitigation is assumed to not include sequestration by geopolymer.)

3.1.1.2. Process complexity [flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option]
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Very high complexity due to interconnectedness. FBSR of the supplemental LAW feed requires a large number of integrated unit operations and incorporation of variable streams. The thermal process generates an offgas that both requires extensive treatment prior to release and worker protections to prevent exposure. The process contains many items that require routine hands-on maintenance or replacement; however, the contact-handled nature of the proposed Hanford FBSR LAW would not require remote systems for repairing and replacing equipment in a heavily shielded environment, which has caused limitations for IWTU. The large and extensive treatment system represents an interdependent and complex system. The offgas system is similar to IWTU (without scrubber) and variations have been tested extensively in previous pilot-scale test rigs. The proposed FBSR for Hanford LAW is simpler in that a TO would be used instead of a CRR, which was troublesome during IWTU startup and had refractory issues (Farnsworth et al., 2019). A single unit operation failure in the system will slow or delay operations or even shut down the system. Consequence: Challenging to run system, delayed processing, additional costs, missed milestones.

3.1.1.2.1. Unit operations (21 systems listed below)[6]

- Feed preparation tasks
  - Clay feed system
  - Waste staging, mixing feed system (moderate complexity)
  - Additive feed system
  - Gas supply systems
- FBSR system
  - DMR (high complexity)
  - Spray nozzles (moderate complexity)
  - Process gas filter
  - Steam supply

[6] Very low or low complexity/consequences unless specified otherwise.

- Offgas system
  - Thermal oxidizer
  - Cooler
  - Carbon bed
  - Wet scrubber (if needed)
  - Reheater
  - Pre and HEPA filters
- Solids handling
  - Product handling system (moderate complexity)
  - Geopolymer additive system
  - Geopolymer mixer
  - Geopolymer product packaging
  - Geopolymer storing/curing
  - Container swabbing and decon station
  - Container load out station.

3.1.1.2.2. Accuracy of controls needed

- Sampling/measurements needed to control process – Very high complexity. Batch qualification is expected to give composition for clay/alumina amount where clay content and type are adjusted to account for alumina in the LAW (SRNL-STI-2011-00387). Process variability vs. clay/alumina composition and operating conditions has not been tested for a designated set of waste compositions to consistently achieve an acceptable crystalline structure (e.g., sodalite and nosean may form a solid solution; however, they are isostructural and contain a cage that could isolate CoCs). Consequence: Potential low throughput; poor product quality.

- Modeling needed to control process – Very high complexity. The FBSR process is driven by compositional requirements to produce a durable waste form (equivalent to the Na_2O-Al_2O_3-SiO_2 chemistry "shown to be acceptable" in 2001 with Tank AN-107 simulants) that is flowable, free of secondary phases, and of reliable durability. Reactions in the DMR gas phase occur within seconds, requiring a constantly vigilant process control system. Consequence: See items below. After solid phase measurements have confirmed inferences from leaching data of structural incorporation of ^{99}Tc and ^{129}I (with additional, supporting lines of evidence) and reoxidation of the granular waste form has been evaluated, a defensible product control system that accommodates variabilities and uncertainties in inputs (e.g., feed compositions), clay additives, etc. could be developed using the MINCALC™ system as a reasonable starting point.[7]
  Expect FBSR is moderately robust toward composition and operation with few parameters needed. Testing assumed during development would be used to develop/refine models/control process.
  - Failure modes for improper operation
    - Improper mineralized product production

[7] The evaluation of the long-term performance of the resulting steam reforming products (e.g., in a PA) would benefit greatly from additional information on the thermodynamic and rate model parameters needed to represent the dissolution of the steam reforming waste form in a PA to calculate a fractional release rate.

- Producing wrong mineral product or an amorphous product due to inability to control additives and process conditions would impact leachability and long-term performance of the radionuclides and metals from the waste form product.

– Off-normal waste feed composition
  - Variations in ratios of concentrations of elements captured in the primary waste form (e.g., sodium, chromium, halides, radionuclides) and their potential interactions can lead to variations in the primary waste form chemistry and mineralogy that may impact waste form performance.
– Improper coal/oxygen addition
  - Excess coal/insufficient oxygen addition causes higher levels of unreacted coal in the primary waste form and operating changes in the TO.
  - Insufficient coal/excess oxygen causes incomplete nitrate/NO_x destruction.
– Improper clay addition
  - Improper amount of clay results in inadequate mineral product formation, or higher volumes of primary waste form. Note that most of the pilot-scale studies were run using excess clay; however, subsequent BSR testing demonstrated that excess clay was not needed…[and helps] maximize Na_2O waste loadings (SRNL-STI-2011-00387 [p. 53]).
– Failure to control key temperatures in the DMR, PGF, TO, and offgas system
  - Temperatures too low could cause off-specification mineralized product, incomplete nitrate/NO_x destruction, incomplete organics/H_2 destruction, particulate filtration failure, or creation of aqueous secondary condensate.
  - Temperatures too high could cause filter failure, refractory failure, higher NO_x emissions, DMR slagging or fouling/scaling.

3.1.1.2.3. Commercially available/similar (of a type) to available/bespoke systems – High number of custom components. The supplemental LAW FBSR facility would be first-of-a-kind, but some components are used in related or other systems in use (e.g., product handling and packaging system, PGFs, GAC bed, and process blowers at IWTU). Thus, many of the IWTU lessons learned would be applicable, including ceramic PGFs and nozzle design. Entirely or relatively new for this application: DMR producing durable mineralized product; spray nozzles for an alkaline clay slurry; product handling system; configuration and integration of offgas system, geopolymer monolithing system; (and perhaps refractory lining of DMR). Consequence: Need to redesign/rebuild, causing mission delays.

3.1.1.2.4. Overall flowsheet integration complexity – Very high overall complexity. The flowsheet for an FBSR facility for supplemental LAW treatment is more complex than for a grouting facility and of similar complexity when compared to vitrification. The waste feed system includes batch analysis and metered addition of clay based on the feed analysis to produce the desired mineralized waste form with highest practical waste loading.

Multiple waste feed nozzles are used to feed the DMR, which has several other gaseous (steam, nitrogen, oxygen) and solid (coal) inputs; the feed rates of which must be controlled to maintain DMR operation within fluidized bed hydrodynamic and stoichiometric limits.

The mineralized product handling system includes equipment for collecting, pneumatic transferring, and cooling the mineralized product so that it can be formed, with geopolymer additives, into the geopolymer monolith product, in containers for storage, transport, and disposal.

The offgas system includes high and low-temperature (HEPA) filtration, thermal oxidation, GAC bed mercury absorption, wet scrubbing, and offgas cooling and reheating. The recycle of spent scrubber solution to the feed system can tolerate some additional variability to the waste feed composition that must be accounted for in the feed analyses and clay additive determinations.

Operating experience from WTP LAW Vitrification Facility will help with some design and operation that FBSR has in common with vitrification, including waste feed staging and mixing, the carbon bed, and HEPA filtration. IWTU operating experience will help with the DMR, PGF, product handling system, offgas cooler, carbon bed, and HEPA filtration. Industrial and commercial operating experience in other industries will help with design and operation of some FBSR unit operations, including liquid, solid, and gas transport (feed and product systems), product monolith (grouting) system, product storage and curing, and thermal oxidation. Consequence: Delayed processing, complex interrelated systems, DMR idling causing variability in waste form composition. Mitigated by experience at IWTU and years of testing assumed performed prior to construction.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed) – FBSR requires extensive utilities, including large demands for steam, cooling water, liquid oxygen, and liquid nitrogen, and process chemicals such as clay, coal, alumina, TO fuel (propane, natural gas, or fuel oil), sulfur-impregnated activated carbon, HEPA filters, and geopolymer additives (clay, sodium silicate, and NaOH).

Operating experience from IWTU, presuming it continues on its startup/operation path, would be applicable for all of this infrastructure except for the clay additive, TO fuel, and geopolymer additives. The infrastructure for the clay, TO fuel, and geopolymer additives is similar to relevant infrastructure in other industries. Cross-site supernatant liquid transfer line is needed to support this alternative.

Consequence: Delayed processing, complex interrelated systems, DMR idling causing variability in waste form composition due to addition of alumina (if the DMR is idled for 1-2 days based on IWTU experience but perhaps longer for the mineralized product) and continued addition of coal/oxygen/steam to maintain bed fluidizing; also causes attrition of particles in bed. If shutdown is required, can impact schedule and primary waste form properties. Further risk mitigation is provided in planned process demonstration at pilot- and demonstration-scale prior to full-scale supplemental LAW treatment system design.

3.1.1.4. Required demolition/removal/modification – It is expected that siting will not require demolition or removal of existing facilities. No consequences.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: Being completely ready to requiring development to make process work.] – Some aspects demonstrated. The FBSR alternative will use a new flowsheet and approach. Portions of the process have been tested using pilot- and full-scale systems. Uncertainty remains in the partitioning of selected species and in the long-term performance of essentially every FBSR unit operation which, while represented in other systems – including the WTP LAW melter systems and IWTU, Irwin, and pilot-scale simulant testing – will need to operate with the specific design and operation for supplemental LAW treatment. Consequence: Delayed processing and higher costs due to either process stoppage for redesign and process changes, or to more frequent or longer downtime for maintenance.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list) [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Low robustness. Recovery actions from things that go wrong include slowing or stopping the feed while performing corrective actions, process shutdown for redesign and process changes, or more frequent or longer downtime for maintenance. Based on prior FBSR experience at IWTU, unit operations most prone to failure or at least frequent maintenance include the feed systems, PGF, and product handling system. Consequence: Delayed processing and higher costs. Some mitigation by pilot-scale testing that would be performed prior to final design and operation.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques, place the waste form in HICs, or better isolate the waste form in IDF. Consequence: Retrieve the containerized material for alternate disposal or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions and flowrates
[High heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – Moderate adaptability. The ability to adjust waste loading and clay/alumina amounts (where clay content and type are adjusted to account for aluminum in the LAW feed) would allow an FBSR facility to handle a wide range of feeds. NRC (2011) concludes "…crystalline ceramic waste forms produced by FBSR have good radionuclide retention properties and waste loadings comparable to, or greater than, borosilicate glass."

However, the Hanford LAW compositions tested to date do not adequately represent those likely to be treated and more work (e.g., based on designed experiments) would help demonstrate process capability. Non-pertechnetate is not an issue for the FBSR process since any non-pertechnetate would likely react to form Tc(VII) in the DMR. Consequence: Delayed processing and higher costs. Mitigated by ability to analyze and blend waste feed in the feed system, use of two FBSR systems where one could be shut down for maintenance or during times of reduced demand.

3.1.4. Ability to incorporate future advances

[MOE: Easily incorporated to impossible.] – Moderate adaptability. The high capital cost and unique operations makes incorporation of future advances challenging. Consequence: High cost of changes.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.] – FBSR uses commonly available feed and start-up bed materials – water, steam, clay, coal, alumina, TO fuel (propane, natural gas, or fuel oil), sulfur-impregnated activated carbon, HEPA filters, and geopolymer additives (clay, sodium silicate, and NaOH). These are all common commercial and industrial materials. The likelihood of failure to resource constraints is low. The consequence of failure due to a constraint on any one of more of these materials is also low. For example, if one coal or clay becomes unavailable, then another of many other coal and clay options that have already been studied could be used. If one fuel for the TO becomes unavailable, other fuel options, some already studied, could be used.

3.2.1. Annual average spending

[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – The funding needs for a supplemental LAW FBSR facility will likely exceed the annual benchmark funding for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW only) against benchmark annual supplemental LAW treatment budget] – The peak funding needs for a supplemental LAW FBSR facility will likely greatly exceed the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – FBSR facilities can operate at perhaps ~10–20% of the design feed rate, but have limited ability to operate at lower rates. Idling the DMR at temperature with no waste feed is practicable for up to ~1–3 weeks but would require adding fluidized bed media to account for attrition and would cause contamination of the treated product with non-rad added bed media. The steam reforming equipment can be powered down almost instantaneously. The cold shutdown time for the Hanford LAW FBSR would be controlled by the cool down rate for the DMR because a TO would be used. Based on IWTU experience, it would likely take 2-3 days to go from operation for cold shutdown for the proposed Hanford LAW FBSR facility. Startup taking ~1-2 weeks would be a reasonable estimate for the proposed Hanford LAW FBSR facility. Using two FBSR facilities provides more flexibility than one because one or both can be operated at higher or lower feed rates, on idle (for up to about 1-3 weeks, or shut down, to match changes in feed supply.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – High potential failure is assumed to be caused by a lack of funding, and the failure point would occur during construction at peak spending. Consequence: Delayed mission due to lack of funding, delayed start of supplemental LAW treatment processing. Moderate amount of funding spent and time consumed prior to funding failure.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility starts and stops prior to startup. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to FBSR option, construct, and then funding is not allocated for startup. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – The supplier used for the FBSR is a single U.S. vendor that could go out of business. Consequence is DOE would assume the technology ownership and continue operations, potentially causing additional cost and delays. Calcined coal is typically added directly to the DMR bed as a fuel source and a reductant (SRNL-STI-2011-00387); however, the calcined coal used in IWTU has a single source in China. This supply chain should be evaluated if FBSR is selected for Hanford supplemental LAW treatment.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $5,527 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$3,375 M (includes commissioning costs)

4.2. Operations costs

$2,152 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

C.2.12 Selection Criteria Assessment for Alternative Grout 4B

Alternative Grout 4B: Off-site Vendor for Grouting with Off-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

Note: This evaluation assumes that the vendor performs the grouting process (i.e., it is essentially identical to Grout 1B alternative in operations and product, and only differs in location of the immobilization step).

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents – to all retained–to–amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over the long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for the long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for the long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.1.2. Technetium (non-pertechnetate will be evaluated below in confidence) [MOE is projected concentration in groundwater.] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site. BFS sequesters technetium.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3.1.3). No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection.] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives; ammonia stripped during evaporation is immobilized at ETF.] – Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives. No significant amount of residual ammonia in grouted tank wastes. Minimal impact to Hanford groundwater due to grouted ETF solids from on-site supplemental LAW evaporator. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements. Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be TCLP compliant (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory. Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.2. Chromium – Cr(VI) sequestered by redox reductants in BFS and precipitation as hydroxide with alkali. Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.3. Other [No MOE needed.] – Grout waste form will be TCLP-compliant (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include the evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS.

1.2. Long-term risks upon successful completion
[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentrations of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed (RPP-RPT-64064, *Distribution of LDR Organic Compounds in Hanford Tanks Waste and the Implications to LAW Treatment by Cementitious Solidification/Stabilization*); additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in speciation in waste as predominantly pertechnetate with a small fraction of non-pertechnetate in most tanks. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.3. ^{79}Se – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.4. Nitrates/nitrites – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – High confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.2. Chromium – High confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.3. Other RCRA metals – High confidence in ability to pass TCLP/waste acceptance criteria. Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria.

1.2.3. Confidence in total volume of primary and secondary waste forms produced
High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk.

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage.] (See tank leak discussion in Volume I, Section 1.3.3 for more detail.) – Startup in ~5 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~5 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is less impactful because it does not rely on the cross-site transfer line and is more flexible in specific feed piping, tank utilization, etc. As this applies to both 200 West and East Area facilities, it is less directly dependent on specific infrastructure, including DSTs, and would therefore be less impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing the risk of tank leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction near an operating radioactive facility. Some worker exposure to radioactive liquids due to loading/unloading liquid in truck.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (High consequence hazard is not applicable to this alternative since there is no vault.) Over 20 years of operation of saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)] – Moderate risk. High number of radioactive transports. No transports of raw materials onto site; no hazardous liquid chemicals shipped onsite; many radioactive liquid transports of treated supplemental LAW offsite; radioactive liquid transport of evaporator condensate to ETF (assumed to be by truck); many off-site transports of solid radioactive materials (grouted waste) from vendor to off-site disposal facility.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to high discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; evaporator condensate collected to LERF/ETF (~38% of feed volume[2]) containing radioactive and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC-filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Few tanks and process unit operations onsite. Risk of liquid spills during transport of both supplemental LAW to off-site vendor and evaporator condensate to LERF/ETF. Mitigated by experience with shipment of radioactive liquids.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – Low risk of liquid spills during transport of liquid decontaminated supplemental LAW to off-site vendor.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment].] – Minimal solid waste; some equipment and job control waste. Evaporator condensate to LERF (380,000 gallons per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions

[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gallons of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals, assuming that the vendor requires the same amount of electricity and grout formers as was calculated for the Grout 1A alternative (RPP-RPT-63426).

[2] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

There would be additional emissions from transport of liquid to the vendor and then shipping offsite. Expect shipments of ~46,000 grouted waste form boxes to distant disposal location(s) (see Volume II, Section H.9 for more information).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~5 years – Vendors are available with the ability to perform this operation with existing facilities. Time to startup will be a function of the readiness of the Hanford Site to ship material to the vendor and the permitting required to process and dispose of the waste.

2.4.2. Duration to full capacity (additional years) 0 years – Vendors are available with the ability to perform this operation with existing facilities.

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risks of additional mission delays.

2.4.4.1. Delays due to technical/engineering issues – Minimal risk to delay operations; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*),and mitigation is to send noncompatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk of delay. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed of waste). [MOE: Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, but engineering uncertainties are minimal. Uncertainty remains in LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence is reduced waste loading or diverting more waste to LAW melters or vendor treatment.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (by changing grout or GFC recipe, etc.) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading.

3.1.1.1.2. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping.

3.1.1.1.3. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidization methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility but impacts in process delays could occur. Mitigation is potential for off-site vendor treatment.

3.1.1.1.4. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Consequence: Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[3]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment – Metered additions, mechanical mixing, potential offgas generation.

[3] Very low or low complexity/consequences, unless specified otherwise.

- Receipt/storage tank (agitated, cooled?) – Vessel with pumps.
- Receipt tank (agitated, cooled?) – Continuous stirred tank reactor vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container box disassembly and emplacement at off-site location(s) – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition. Moderate consequences.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed overcapacity design of system, lessons learned from SRS or other sites. The use of an off-site grouting facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduces SST leakage risk; reduce cross-site transfer of supernatant liquid.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Only building Tank Farms Pretreatment (TFPT)/LDR evaporator and liquid load-out facility onsite.
- Utility usage (electrical, cooling water, steam, etc. is low).

- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that require diversion.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed.

3.1.1.5. Technology maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990), INL, etc. (including containerized grout). Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for Defense Waste Processing Facility [DWPF] effluents). Alternative assumes that vendor can produce viable waste form. Consequence: Additional development time needed, delayed processing. Moderate consequences.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Very high robustness. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative. Low consequences.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, etc.). Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Unlikely vendors need to expand capacity but expect that vendors could handle variability in flow rates so expansion unlikely to be needed. Some vendors may need permit changes. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending

[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for off-site immobilization will likely be beneath the annual spending benchmark funding level ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for off-site immobilization will likely be beneath the benchmark funding level ($450M/yr).

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] Very high flexibility. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] Scenario is operations more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Operation does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. Sufficient funds would likely be available to perform this alternative by the project need date.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production.] Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only (e.g., off-site vendor; special ingredient; sole source provider). – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. If the vendor is unable to perform the task, another vendor could be selected.

Off-site disposal location could cease receipt of waste or permission to transport is revoked for unforeseen reasons. Consequence: The process impact would be a delay in processing until an alternative is identified or if an ingredient cannot be procured and one has not been pre-selected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process. A ~2.5-month working inventory of material would remain onsite at the vendor or in-transit until the issue is resolved (maximum of 750 containers).

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. All costs are discounted at 3% rate.

Total: $3,854 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$410 M (includes commissioning costs)

4.2. Operations costs

$3,444 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

C.2.15 Selection Criteria Assessment for Alternative Grout 6

Alternative Grout 6: Phased Off-site and On-site Grouting in Containers

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents - all retained – to amount increased by treatment.] – Applicable to all three phases.

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; All alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for the long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides [MOE: Estimated peak groundwater concentration at compliance point over ~1,000 years (e.g., DOE O 435.1; IDF PA compliance point and period); identify peak to 10,000 years to address longer-term groundwater protection (e.g., post-compliance period).]

1.1.2.1.1. Iodine – Onsite: Iodine mobility to ground water is limited during the first 1,000 years compliance period. Iodine sequestered by getter leads to enhanced retention in waste form; relative to non-getter waste form. Projected ~100× below DWS (maximum contaminant level) per NDAA17 report but uncertainty in long-term performance with only laboratory data to date. Iodine not bound to getter could exceed DWS.

To limit mobility beyond the period of compliance, iodine requires stability of getter phase to meet concentration limits.

On-site inventory from supplemental LAW reduced by ~50% or more. Inventory remaining onsite is assumed to scale proportionally to peak dose at point of compliance. Offsite: No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.1.2.1.2. Technetium – Onsite: Technetium mobility to ground water is limited during the first 1,000 years (compliance period) due to facility performance. BFS sequesters technetium providing high performance for technetium; ~10× below DWS per NDAA17 report; uncertainty in rate of reoxidation of grout in IDF; an oxidized grout could exceed DWS. To limit mobility beyond the period of compliance, technetium requires maintaining reducing conditions for a portion of the waste form during disposal to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout. On-site inventory from supplemental LAW reduced by ~50% or more. Inventory remaining onsite will scale proportionally to peak dose at point of compliance. (Non-pertechnetate will be evaluated below in confidence.) Offsite: No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3.1.3). On-site inventory reduced by this alternative. Offsite: No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Onsite: Nitrate/nitrite mobility to groundwater is limited during the first 1,000 years compliance period. Retained only by diffusion barrier (physical entrapment). Recent diffusivity testing shows some formulations can retain nitrate/nitrate more effectively and estimate peak concentrations below the compliance standard. These tests were performed in a conservative, saturated environment, which would produce much greater release rates than actual unsaturated conditions in the IDF.

Conservative assumptions regarding nitrate/nitrate subsurface behavior could result in exceedance of DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3). On-site inventory reduced by this alternative in roughly the same fraction as the disposed volume.

Offsite: No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting the site's license requirements.

1.1.2.3. Ammonia – Onsite: No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; ammonia stripped during evaporation is immobilized at ETF.] Ammonia from this option is low in the grouted secondary waste disposed of in IDF but ammonia will still be present from LAW melter system so is not differentiating among alternatives. Offsite: Minimal impact to Hanford groundwater due to grouted ETF solids. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting the site's license requirements.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Mobility judged against TCLP, which reducing grout consistently passes. Onsite: Waste form has reduced toxicity. Grout waste form would be compliant. Offsite: Grout waste form would pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory. Onsite: Sequestered by sulfide reaction with BFS. Offsite: Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form (grout redox chemistry).] – Onsite: Cr(VI) sequestered by redox reactions with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty exists in rate of reoxidation of grout in IDF and change in waste form pH; an oxidized, neutral grout could exceed DWS for chromium. To limit mobility beyond the period of compliance, chromium requires maintaining reducing conditions for a portion of the waste form and maintaining alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond the period of compliance. Offsite: Grout waste form would pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.3. Other [No MOE needed.] – Onsite: Projected concentrations of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium. Offsite: Grout waste form would pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include the evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS. Onsite: Total volume remaining onsite reduced by 30% or more.

1.2. Long-term risks upon successful completion
[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or could be removed/destroyed to beneath regulatory limits, if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and in the resulting waste form as iodide with a fraction of iodate. Moderate confidence in the immobilization of AgI from reaction with getter in the waste form, but any unreacted free iodide/iodate would be mobile. Success of the silver precipitation approach has been shown at the laboratory-scale using getters but not demonstrated at pilot- or process-scale.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

The immobile fractions as AgI can destabilize with time due to chemical reduction of Ag^{+} to Ag^{0} and competition with other species (e.g., sulfide that can form Ag_2S), the rate of these destabilization processes in the disposed waste form is untested. Iodine is a key constituent of interest in the IDF PA.

^{129}I can define waste classification but concentrations in Hanford tanks are likely far lower than Class A limit.[2] Once released by chemical reactions and leached into the subsurface, there is limited to no natural attenuation of iodide, and as such the supplemental LAW iodine inventory could impact groundwater limits in the post-compliance period. However, a complete assessment of iodine impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior) and important uncertainties. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.2. Technetium (including non-pertechnetates) – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste as pertechnetate with a fraction of non-pertechnetate. Within the waste form, there is high confidence in the conversion of pertechnetate to a reduced and insoluble technetium, but there is an unknown behavior of non-pertechnetate. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form could be destabilized with time due to oxidation but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA. Technetium can define waste classification and select tanks have technetium concentrations that approach the Class A limit.[3] However, a complete assessment of technetium impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior) and important uncertainties. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.3. ^{79}Se – Limited to no data available on the speciation in the waste, in grout, or mobility within grout waste forms. Limited attenuation in the Hanford subsurface. High confidence of minimal impact due to minimal inventory (144 Ci or ~2 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*). Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

[2] ^{129}I is listed in Table 1 of 10 CFR 61.55, Waste Classification, that is used to classify wastes for near-surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

[3] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 that is used to classify wastes for near-surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

1.2.2.4. Nitrates/nitrites – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are not retained in grout waste forms and will not be slowed without formulation modification. Nitrate and nitrite are a key constituent within the IDF but will not drive waste classification or waste acceptance criteria.

There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford tanks, and a recent assessment projected concentrations slightly above groundwater limits in the post-compliance period using a projection of a non-optimized grout waste form disposed of in IDF (under saturated, non-conservative conditions resulting in higher than expected release).

As such, there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior) and important uncertainties. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.5. Ammonia/ammonium ion – Onsite: High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal impact. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – High confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation, but low confidence in mercury speciation in tank waste. High confidence in limited subsurface transport and limited knowledge on speciation changes in subsurface.

1.2.2.6.2. Chromium – High confidence in ability to pass TCLP due to sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment and high confidence in knowledge of subsurface mobility; there is limited attenuation in the IDF backfill and subsurface although some mineral interactions (e.g., iron, carbonate, barium) have been observed. Chromate is slow moving in subsurface and expected to be compliant with DWS.

1.2.2.6.3. Other RCRA metals –. High confidence in ability to pass TCLP. Moderate confidence of speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP; however, if Ag is added as iodine getter, this adds uncertainty.

1.2.3. Confidence in total volume of primary and secondary waste forms produced
High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk.
[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage.] (See tank leak discussion in Volume I, Section 1.3.3 for more detail.) – Startup in ~5 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~5 years has lower risk of additional tank leaks because retrievals would be earlier than currently scheduled and would support HLW, allowing the lowest time for additional corrosion-induced tank leaks. This alternative would keep HLW processing on schedule.

Continuity of operations after startup – depending on when an unforeseen event (e.g., tank leak) happens, loss of specific DSTs is more or less impactful. During the initial phase when liquid is shipped offsite, continuity is less dependent on infrastructure items, like the cross-site transfer line. But in later phases when operations transition to on-site production of grout, continuity is dependent on the cross-site transfer line, specific feed piping, tank utilization, etc. Since this has both 200 East and West Area facilities, continuity of operations is directly dependent on specific infrastructure, including DSTs, and would therefore be partially impacted by failure of key staging and transfer tanks.

This alternative is intended to consume the entire initial benchmark supplemental LAW treatment budget and takes advantage of the opportunity for an early start as part of a hybrid or concurrent alternative treatment. There is potential for reducing risk of tank leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety
[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporization of radionuclides. Some construction is near an operating radioactive facility (LAW Vitrification Facility); construction would have shorter duration intervals in comparison to other alternatives.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabrication hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (One high consequence hazard is not applicable to this alternative since there is no monolith in a vault). Over 20 years of operation of saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)]
Large number of transports of raw materials onto site and waste form boxes onsite; large number of radioactive and hazardous liquid transports. Onsite: Large number of solid radioactive waste form packages. Offsite: Many off-site transports of liquid and/or solid radioactive waste form packages to distant location(s). Practical impact would be negligible because transport of low dose solid and liquid radioactive materials is well known.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; all LAW/flush water during grouting is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[4]) containing radioactive and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases likely; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Risk of liquid spills during transport of both LAW to off-site vendor and evaporator condensate to LERF/ETF. Mitigated by experience with shipment of radioactive liquids.

[4] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.3.4. Off-site transportation spills
[MOE: No risk of off-site spills to is high risk for off-site spills.] – Moderate risk of liquid spills during transport of liquid decontaminated LAW for off-site disposal. Large numbers of radioactive shipments, both liquid and (potentially) solids. Mitigated by experience with off-site shipment of radioactive liquids.

2.3.5. Secondary waste streams generated
[MOE: Volume of waste (liquid, solids, and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment] – Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions
[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426). Offsite: Expect shipments of ~15,000 or more grouted waste form boxes to distant disposal location(s) (see Volume II, Section H.9 for more information).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~5 years.

2.4.2. Duration to full capacity (additional years) 1 year.

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delays

2.4.4.1. Delay due to technical/engineering issues – Minimal risk to delay operations; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*)and mitigation is to send non-compatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities is expected to shorten the duration of supplemental LAW (and HLW) processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: tech failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences] Low risk. The grout alternative would use the same flowsheet and approach as the existing SRS facility. Formulations would vary somewhat, and getters would be included, but engineering uncertainties are minimal.

Uncertainty remains in the utility of getters at scale and LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence of failure to identify a suitable iodine getter or remedy results in failure in ability to dispose of waste onsite in IDF and shipping more waste offsite or to the LAW melters.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process would be able to produce an acceptable grout from the entire waste feed vector and to restart quickly from a cold shutdown, which provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives and reduced waste loading.

3.1.1.1.2. Suitable getter (iodine and potentially technetium) not identified/long-term performance inadequate – Medium likelihood and high consequence for on-site disposal of grouted waste. While suitable getters for technetium and iodine have been tested in the laboratory, the application of these getters in a production process and in conjunction with each other has not been demonstrated. Consequence of not identifying suitable getters would be that on-site disposal of the grout is not permitted and other methods to sequester iodine (and potentially technetium) are not identified. Off-site disposal – getter/waste form performance not needed; very low risk.

3.1.1.1.3. Transport lines become blocked/congested or leak – Very low likelihood – Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits, if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility but impacts in process delays could occur. Mitigation is potential for off-site vendor treatment.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk – The LDR organics are assumed to identified during batch qualification and detection limits can be reached for organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Grouting of the supplemental LAW feed requires few integrated unit operations.
The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections are needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – Vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment/load out station – Hoist and forklift operations.
- Container box disassembly and emplacement at IDF – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-spec composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites. The use of an off-site grout production facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduce SST leakage risk; and reduce cross-site transfer of supernatant liquid.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on collocated processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line is not needed to support this alternative.
- Rail line spur.
- Liquid loadout facility.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier. Offsite: Off-site disposal locations may need expansion.

3.1.1.5. Technology Maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Shipping grouted Hanford waste offsite successfully demonstrated during Test Bed Initiative. Grout in general has been demonstrated at scale; saltstone at SRS (similar process, scale, and waste operations since 1990) and INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Adding iodine getters has not been demonstrated at scale. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Consequence: Continue shipping offsite until onsite is available.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, remediating the waste form could be necessary. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (e.g., as a defense-in-depth measure) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Unlikely vendors need to expand capacity but expect that vendors could handle variability in flow rates so expansion unlikely to be needed. Some vendors may need permit changes. Consequence: Minimal cost and short delays. Expect that initial on-site system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays. Additional time to begin on-site disposal allows additional development time.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – The funding needs for a supplemental LAW grout facility would likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr). Spending includes both 200 East Area plant construction while also paying off-site vendor and transporting waste, but benefit is early start.

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget] – The peak funding needs for a supplemental LAW grout facility would likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr). Higher costs overall but could spread costs over one additional year.

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. Grout facilities are typically able to operate below maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.)
Operations, shipping, and disposal are more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and require need to select alternate solution. Off-site disposal option allows flexibility in the event of on-site disposal issues and off-site immobilization step mitigates on-site facility issues. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the on-site facilities does not start or stops until funding is available. Worst case is to continue off-site grout. Consequence: Costs of off-site disposal and grouting must continue longer than projected. Sufficient funds would likely be available to complete a grout capability by the project need date.

3.3. Likelihood and consequences of failing to complete due to unavailability of key services and materials

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).]
Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. If the vendor is unable to perform the task, another vendor could be selected. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been preselected. Offsite: Another disposal location must be identified.

Limited use of sampling because the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. All costs are discounted at 3% rate.

Total: $4,127 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,393 M (includes for commissioning costs)

4.2. Operations costs

$2,734 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

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Appendix D. Summary of Disposal Site, Transportation, and Off-Site Disposal Considerations

D.1 INTRODUCTION

This appendix provides a summary of Volume II, Appendices G and H, which provide detailed additional information on potential waste disposal sites for treated low-activity waste (LAW) and transportation-related considerations for LAW, respectively. A difference between the information in this appendix and in Volume II, Appendices G and H, is that this appendix focuses on the transportation and cost information related to the four alternatives that were evaluated in detail, as discussed below.

LAW immobilized by the alternatives described in this report will be permanently disposed either on or off the Hanford Site. A combination of on-site and off-site disposal is also plausible. The three disposal facilities discussed in Volume II, Appendix G are identified below and are summarized further:

- **Integrated Disposal Facility (IDF)** (Hanford Site) – A U.S. Department of Energy (DOE) facility that is permitted by the Washington State Department of Ecology (Ecology) for disposal of mixed low-level waste (MLLW) from Hanford Site operations, primarily from wastes currently stored in tanks grouped in 18 separate tank farms. This disposal site is applicable to alternatives Vitrification 1 and FBSR 1A, and to the hybrid alternative Grout 6.
- **Energy*Solutions* Disposal Facility** (Clive, Utah) – This disposal facility is commercially operated by Energy*Solutions* and is licensed by the state of Utah (a U.S. Nuclear Regulatory Commission [NRC] Agreement State) and the U.S. Environmental Protection Agency (EPA) to dispose of low-level waste (LLW) and MLLW. This disposal site is applicable to alternatives Grout 4B and the hybrid Grout 6.
- **Waste Control Specialists (WCS) Waste Disposal Facility** (Andrews, Texas) – This disposal facility is commercially operated by WCS and is licensed by the state of Texas (also an NRC Agreement State). This disposal site is applicable to alternatives Grout 4B and the hybrid Grout 6.

For the two off-site disposal sites, transportation programs will be required to ensure safe and secure transport of two LAW waste forms evaluated in this study from the Hanford Site to the WCS Waste Disposal Facility (Texas) and Energy*Solutions* Clive Disposal Facility (Utah). As noted above, the only LAW treatment waste form considered for off-site disposal is grout; therefore, details on transportation and disposal of the fluidized bed steam reforming (FBSR) waste form at those facilities is not discussed. The analysis does address transporting supplemental liquid LAW to an off-site vendor facility for grouting and subsequent transport to Clive and WCS, and for transporting the liquid supplemental LAW directly to the two disposal facilities for both grouting and disposal. The vitrified and FBSR waste forms evaluated in this study would be disposed of onsite in the IDF. The off-site transportation programs incorporate packaging requirements, transportation routes and schedules, documentation, transportation and disposal costs, specific technical considerations, and qualitative risk evaluation.

D.2 DISPOSAL SITES

D.2.1 Integrated Disposal Facility

The IDF, located in the 200 East Area of the Hanford Site, provides a disposal facility for LLW and MLLW. The Hanford Site is located within the Columbia Plateau between the Cascade Range and the Rocky Mountains. This portion of the plateau is also known as the Columbia Basin, as it is a topographically low area surrounded by mountains on all sides. Cataclysmic ice age flooding inundated the area, depositing sediment that is informally called the Hanford formation. The underlying basalts form a block of rock that is surrounded by active fault zones where stresses are mostly relieved. Therefore, stress relief and ground motion on the Columbia Plateau are relatively small.

The IDF is situated approximately 90 to 100 m (300 to 330 ft) above the water table, with the liner approximately 70 m (230 ft) above groundwater. There is approximately 137 to 167 m (450 to 550 ft) of unconsolidated to semi-consolidated sediments over basalt bedrock underlying the disposal site.

Constructed in 2006, the IDF comprises two expandable disposal cells (Figure D-1). Cell 1 is permitted as a dangerous waste landfill under the *Resource Conservation and Recovery Act of 1976* (RCRA), which allows for disposal of radioactive MLLW (WA 7890008967, "Hanford Facility RCRA Permit"). The dangerous waste component is regulated under *Washington Administrative Code* (WAC) 173-303, "Dangerous Waste Regulations," by Ecology. Cell 2 is limited to radioactive LLW only. An update to the waste analysis plan was included in a permit modification request (Vance, 2021) submitted to Ecology in June 2021 and is under review with Ecology. Upon approval, the permit would, among other things, allow disposal of mixed waste in Cell 2 and allow for disposal of secondary waste from the Waste Treatment and Immobilization Plant (WTP) vitrification activities. The radioactive components of both LLW and MLLW are regulated by DOE under DOE O 435.1, *Radioactive Waste Management*. The disposal cells include a leak detection system to collect leachate (WA 7890008967, "Hanford Facility RCRA Permit").

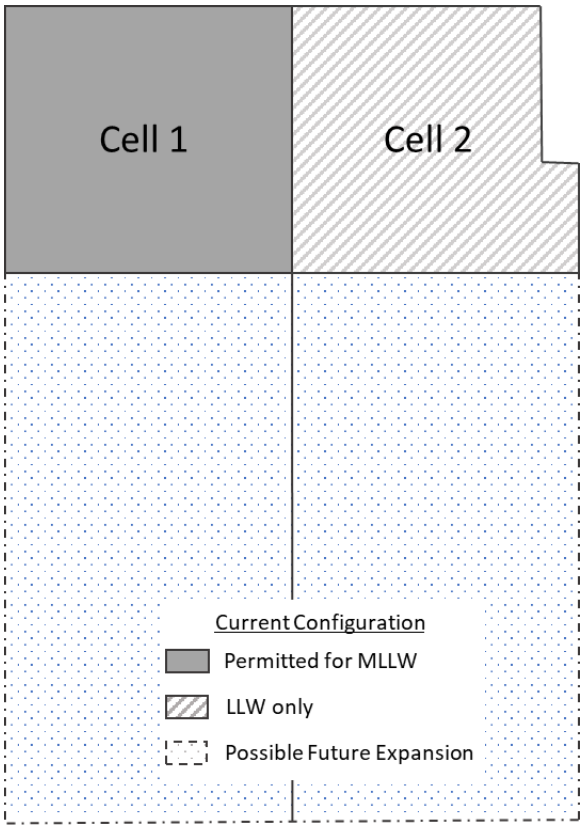


Figure D-1. Integrated Disposal Facility Configuration

Landfill Construction

The IDF liner system includes an operations layer, a leachate collection and removal system (LCRS), a leak detection system (LDS), and a secondary leak detection system (SLDS).

The operations layer, consisting of well-graded granular soil, acts as an insulating layer and protects the underlying liner from damage by equipment and from freezing and desiccation cracking.

Below the operations layer, the LCRS comprises two geotextiles and a gravel layer, followed by a geomembrane liner made of high-density polyethylene and a geosynthetic clay liner that act as moisture barriers. The LCRS is designed so that leachate flows through a perforated pipe above the primary liner into the LCRS collection sump. Below the LCRS is the LDS, which is used to collect any leachate that leaks through the LCRS. The LDS has a similar configuration, as the LCRS (except a composite drainage net) replaces the gravel layer and there is no perforated drainage pipe. The LDS geomembrane liner conveys leachate to the LDS sump for removal. The collected leachate is pumped to two leachate collection tanks until transfer to a treatment, storage, and disposal unit (WA 7890008967).

The IDF liner system also includes an SLDS, which includes an operations layer, drainage gravel, a composite drainage net, and a geomembrane. The SLDS liner is not a regulatory design requirement, but is a redundant leak protection system that collects any leachate that leaks through both the LCRS and LDS. Liquids in the SLDS are removed manually through a portable pump and then transferred to the leachate collection tanks.

Landfill Cover

The final cover design of the IDF has not been completed, but a general conceptual design has been developed. The general design is to cover the IDF with a modified RCRA Subtitle C barrier, which provides a surface barrier for long-term containment, hydrologic protection, and minimizes physical intrusion and recharge. A Subtitle C barrier is the baseline design for a disposal facility containing both dangerous waste (as defined by Washington State regulations) and LLW.

The IDF cover is anticipated to include layers composed of durable material (e.g., topsoil, sand and gravel filter, asphalt base) topped with cover vegetation and a slope (up to 5%) to encourage runoff and minimize the tendency for ponding of rainwater. These layers are intended to divert moisture that may come through the surface barrier away from the trench. The RCRA Subtitle C barrier is to be constructed with a minimum depth of at least 5 m (16.4 ft) to provide shielding from radioactive material and deter intrusion. The cover will include a vegetated surface layer of fine-grained soils to retain moisture, encourage evapotranspiration, and minimize infiltration (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*).

Key Regulatory Requirements

Disposal in IDF requires a determination that the waste incidental to reprocessing (WIR) requirements of DOE O 435.1 have been met, allowing some tank wastes previously managed as high-level waste (HLW) to be disposed of as LLW. In addition, DOE O 435.1 requirements for near-surface disposal of LLW must be met. The LLW requirements are substantially addressed through a DOE Performance Assessment (PA) that evaluates the long-term impact of near-surface disposal through computer modeling analysis, to provide DOE with a reasonable expectation that LLW and MLLW disposal will meet the radiological performance objectives documented in DOE M 435.1-1, *Radioactive Waste Management Manual*.

Because IDF construction, operations, and closure occur under DOE's regulatory authority under the *Atomic Energy Act of 1954* (AEA), it is not required to meet NRC's LLW classification system at Title 10, *Code of Federal Regulations*, Section 61.55 (10 CFR 61.55), "Waste Classification;" however, as noted below, the waste acceptance criteria for the IDF contains limits for waste to be accepted.

In accordance with the criteria set forth in DOE M 435.1-1, a final WIR evaluation (DOE-ORP-2022-03, *Final Waste Incidental to Reprocessing Evaluation for Vitrified Low Activity Waste and Secondary Waste at the Hanford Site, Washington*) was prepared to address the waste from the Hanford Site underground tanks that will have key radionuclides removed to the extent practical, be stabilized via vitrification to be at Class C levels or less, and meet the IDF waste acceptance criteria.

Performance Assessment

In 1999, the initial PA for the IDF (DOE/RL-97-69, *Hanford Immobilized Low-Activity Tank Waste Performance Assessment*) was approved, followed by an update in 2001 (DOE/ORP-2000-24, *Hanford Immobilized Low-Activity Waste Performance Assessment: 2001 Version*). Additional revisions to the PA were deferred until completion of DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC&WM EIS), in 2012. This EIS resulted in a Record of Decision (78 FR 75913, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington, Record of Decision") to implement disposal of the following waste types in the IDF:

- LLW and MLLW from tank waste treatment activities generated from the WTP
- On-site non-CERCLA non-tank waste
- Fast Flux Test Facility decommissioning waste
- Effluent Treatment Facility-generated solid secondary waste

- On-site waste management waste.

Based on the Record of Decision, a new PA was prepared to examine the long-term effects associated with the planned waste types. The current PA for the IDF (RPP-RPT-59958), was publicly released in 2019 and includes computer modeling of the near-surface disposal of LLW and MLLW at IDF.

DOE LLW disposal requirements in DOE M 435.1-1 require that a PA "must provide reasonable expectation that the facility will not exceed the performance objectives for a period of 1,000 years following closure of the facility." The 2019 IDF PA included analyses for the required 1,000-year period, but also from 1,000 to 10,000 years, and an extended runout to 500,000 years after closure. The IDF PA has been reviewed and approved by DOE, and an Operating Disposal Authorization Statement has been issued, licensing IDF for disposal of radioactive materials for vitrified primary waste and grouted secondary waste.

Although the most current revision of the IDF PA was completed in 2019, the technical basis supporting the PA is maintained through continued updates that evaluate changes to the PA inputs and assumptions. An annual assessment of these changes is performed to ensure that the conclusions of the PA are still valid.

Overall, groundwater models predict compliance with the 1,000-year performance objectives. Within the 10,000-year period, models predict compliance with performance objectives, with ^{99}Tc and ^{129}I as the primary contributing dose to a representative member of the public. For the atmospheric pathway, the PA shows the IDF meets the performance objectives for the 1,000-year post-closure period.

In addition to assessing pathways, an analysis was performed to calculate the dose equivalent for a future member of the public that intrudes on the IDF. This type of scenario is used to establish radionuclide concentration limits for disposal. In the IDF PA intruder scenario, a hypothetical driller of groundwater uncovers waste disposed of in the IDF. Both acute and chronic exposures were considered and evaluated for up to 1,000 years after closure of the IDF, following at least 100 years of institutional controls. Based on these analyses, the three chronic exposures scenarios evaluated (rural pasture farmer, suburban garden resident, and commercial farm worker) were below the 100 mrem chronic dose performance measure and the acute well driller scenario dose was below the 500 mrem acute dose performance measure.

Waste Acceptance

A waste acceptance criteria document for the IDF has been finalized and defines the acceptance criteria for LLW and MLLW, and the requirements for complying with the IDF Disposal Authorization Statement (Gilbertson, 2021) per DOE M 435.1-1 and RCRA permit (Vance, 2020). The waste acceptance criteria prohibit HLW from acceptance and disposal at IDF.

The IDF is permitted by Washington State as Operating Unit Group 11 under Revision 8c of the Hanford Facility RCRA Permit. Currently, the IDF permit authorizes disposal in only one cell (Cell 1). Cell 1 is permitted to dispose of MLLW, limited to immobilized LAW from WTP, immobilized LAW from the demonstration bulk vitrification system, and IDF operational wastes (WA 7890008967).

Currently, waste acceptance criteria for the IDF includes the following requirements:

- Wastes must be compliant with RCRA Land Disposal Restrictions (LDR) (40 CFR 268, "Land Disposal Restrictions").
- Transuranic wastes are prohibited.
- Free liquids are prohibited, unless one of the provisions in the following section of WAC 173-303-140(4)(b)(ii) can be met.
- Pre-waste acceptance is required; waste pedigree needs to be verified by IDF personnel.
- Comply with the maximum void space requirements for containers (i.e., must be >90% full).

Dangerous waste performance information has been included in the DOE-mandated PA required by DOE M 435.1-1 (RPP-RPT-59958). This PA is required for analysis of radioactive constituents, although an assessment of dangerous waste was included to meet the IDF RCRA permit condition. One aspect of the permit is creation and maintenance of a Risk Budget Tool to model future impacts of the planned IDF waste forms to the vadose zone and groundwater, such that if modeling results are within 75% of a performance standard, the permit requires DOE and Ecology to discuss mitigation measures or modified waste acceptance criteria (IDF RCRA permit condition III.11.I.5.a.ii). Additional waste analysis and acceptance permit conditions may be included upon approval of the permit modification request. Grouted waste forms from supplemental LAW treatment are not included in the list of waste streams currently approved for disposal in the IDF RCRA permit or the DOE M 435.1-1 Disposal Authorization Statement (Gilbertson, 2021).

Waste Capacity

Plans for the IDF include future construction to expand the disposal cells to a length of 501 m (1,645 ft) and width of 410 m (1,345 ft) at ground level, with a depth of 12.8 m (42 ft). The IDF PA assumes that waste loading will comprise 40% of the total available IDF capacity, with the remainder consisting of backfill. This results in a maximum waste disposal capacity of 900,000 m^3 (1,200,000 yd^3) (RPP-RPT-59958).

System Plan (ORP-11242, *River Protection Project System Plan* [Rev. 9]) waste disposal volumes were estimated for several scenarios that evaluated different volumes split between first LAW and supplemental LAW capacities. Volumes of both vitrified waste and grout for the supplemental LAW volume were presented and used to compare the volumes disposed of onsite in the IDF in the various alternatives (Table D-1). The baseline case, Scenario 1, in the System Plan considers a split of 59% to first LAW and 41% to supplemental LAW. The presented values are based on this scenario, where the IDF capacity is not exceeded in any cases. Note that one scenario (Scenario 3) presented in the System Plan would exceed the IDF capacity, where over 72% of the treated LAW feed is directed to supplemental treatment.

Based on this data, all supplemental LAW treatment technologies would produce waste within the waste disposal capacity of IDF (Table D-1).

Table D-1. Estimated Disposal Volumes to the Integrated Disposal Facility

Waste Type	System Plan[a]	LAW Supplemental Treatment Alternatives[b]		
	Scenario 1 m^3 (yd^3)	Grout Onsite m^3 (yd^3)	Grout Offsite m^3 (yd^3)	FBSR m^3 (yd^3)
Immobilized LAW	190,074 (250,097)[c,d]	112,143 (147,557)[e]	112,143 (147,557)[e]	112,143 (147,557)[e]
Grout (primary waste)	0	304,000 (400,000)[f]	0	0
FBSR	0	0	0	202,667 (266,667)[g]
Secondary waste	41,397 (54,469)	24,424 (32,137)	24,424 (32,137)	28,072 (36,936)[h]
Total | % IDF capacity	**231,471 (304,567) | 26%**	**440,567 (579,693) | 49%**	**136,567 (179,693) | 15%**	**342,882 (451,161) | 38%**

[a] ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

[b] Secondary waste volumes calculated based on the assumed ratio of secondary waste projected for the full immobilized LAW inventory in the IDF PA, Table 3-26 (0.218 ratio) (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*).

[c] Taken from Scenario 1 of ORP-11242 [Rev. 9], Table ES-4, assumes 5.51 MT of immobilized LAW per container and a density of 2.58 kg/L (MT/m^3) for the LAW glass.

[d] The LAW supplemental treatment alternative Vitrification 1 would result in equivalent waste disposal volumes as the IDF PA Baseline Case.

[e] Based on the amount of WTP LAW glass, assuming 41% of volume is attributed to supplemental LAW (assumed in Scenario 1 of System Plan [Rev. 9]).

[f] Taken from Scenario 1 of ORP-11242 [Rev. 9], Table ES-4.

Table D-1. Estimated Disposal Volumes to the Integrated Disposal Facility

Waste Type	System Plan[a]	LAW Supplemental Treatment Alternatives[b]		
	Scenario 1 m^3 (yd^3)	Grout Onsite m^3 (yd^3)	Grout Offsite m^3 (yd^3)	FBSR m^3 (yd^3)

[g] Calculated based on the grout volume for supplemental LAW from ORP-11242 [Rev. 9], Table ES-4, and assumes the volume multiplier of waste to grout as 1.8, and of waste to FBSR product as 1.2. (Note that the liquid-to-solid volumetric ratio was conservatively assumed to be 1.2 in transport and disposal calculations related to FBSR. The larger ratio results in a larger FBSR waste volume. The FBSR volumetric ratio assumed in all other analyses discussed in this report was 1.0.)

[h] FBSR assumes a ratio of 0.018 units of secondary waste per unit of primary waste generated (RPP-RPT-63580, *Calculating the Non-Monetary Impact of Operating a Fluidized Bed Steam Reforming Facility*) and added to volume of secondary waste from vitrification.

FBSR = fluidized bed steam reforming.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
PA = performance assessment.
WTP = Waste Treatment and Immobilization Plant.

D.2.2 Energy*Solutions* Disposal Facility (Clive, Utah)

Energy*Solutions* operates a low-level radioactive waste (LLRW) disposal facility west of the Cedar Mountains in Clive, Utah. Clive is located along Interstate 80, approximately 4.8 km (3 mi) south of the highway in Tooele County. The facility is approximately 80.5 km (50 mi) east of Wendover, Utah, and approximately 128.7 km (80 mi) west of Salt Lake City, Utah. The natural topography slopes slightly toward the southwest with approximately 3 m (10 ft) of relief from the northeast corner of the section to the southwest corner of the section. An aerial view of the facility is shown in Figure D-2.

Figure D-2. Aerial View of the Clive Facility

The initial selection of the site location dates back to the late 1970s when DOE and the state of Utah began the cleanup of an abandoned uranium mill site. The Vitro mill site, located in central Salt Lake City, was one of the first sites cleaned up under the DOE Uranium Mill Tailings Remediation Action (UMTRA) Program. DOE investigated 29 sites to identify the safest permanent disposal site for these materials. After 8 years of characterization and evaluation of several sites, DOE selected the Clive site located in Utah's West Desert. The site's remote location, low precipitation, general absence of groundwater, and low-permeability clay soils were some of the attractive qualities of the area.

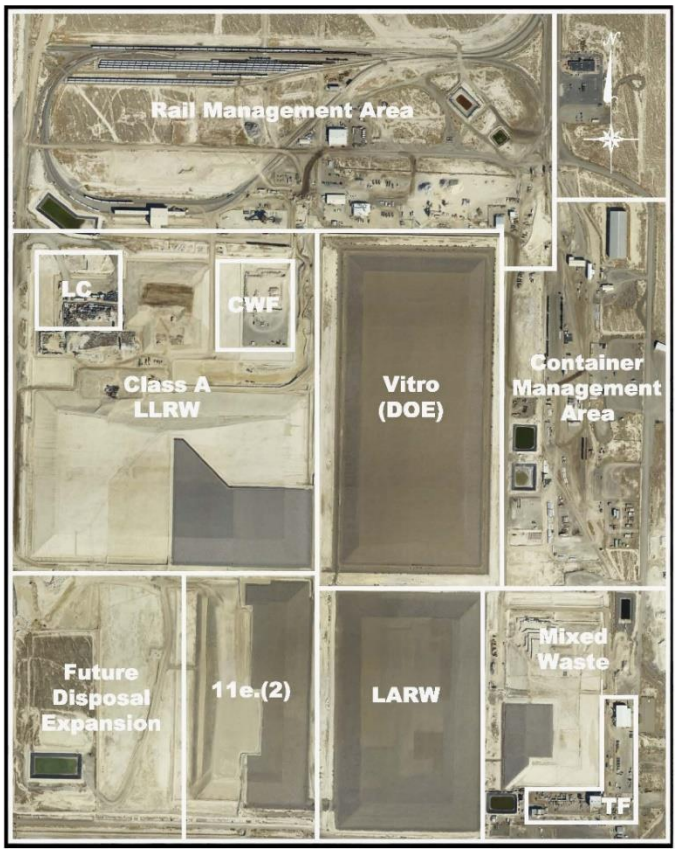
From 1984 to 1988, the Vitro tailings were relocated to Clive and placed in an above-ground disposal cell. Since acquiring land adjacent to the Vitro disposal embankment and obtaining a disposal license, the vision of the Energy*Solutions* Clive facility has been to provide a private disposal option for material from government and commercial environmental cleanups and generators of radioactive waste in separate disposal embankments similar to those used for DOE's Vitro project.

The Clive facility has received waste from cleanup activities carried out across the country, including projects by the EPA, DOE, U.S. Department of Defense (DoD), utilities, and other commercial entities. The initial disposal license was for naturally occurring radioactive material (NORM). Since 1988, the Energy*Solutions* radioactive material license has been amended several times, expanding the types of radioactive materials to include Class A LLRW, in addition to NORM.

The facility is 2.6 km^2 (1 mi^2) in size. The DOE-owned Vitro property occupies approximately 100 ac of the facility. Figure D-3 shows the disposal cells and major man-made and topographic features at the facility. The facility is accessed by both road and rail transportation.

Energy*Solutions* began waste disposal activities at the facility in 1988. At present, waste is placed in one of three disposal embankments: Class A West (CAW), mixed waste, or 11e.(2). A fourth embankment, the low-activity radioactive waste (LARW) embankment, located between the mixed waste and 11e.(2) embankments, was closed in October 2005. On November 26, 2012, the Utah Division of Radiation Control approved an amendment to the Energy*Solutions* radioactive material license UT 2300249, "Radioactive Material License Number UT 2300249," to combine the Class A and Class A North embankments into the CAW embankment.

The CAW embankment contains the large component disposal area and the Containerized Waste Facility. In the north-central part of the facility, DOE has disposed of the Vitro uranium mill tailings. This area is owned and monitored by the DOE.



Source: Figure 1 of Energy*Solutions*, 2015, *Bulk Waste Disposal and Treatment Facilities Waste Acceptance Criteri*a, Rev. 10, Energy*Solutions*, Salt Lake City, Utah.

Figure D-3. Clive Facility Disposal Cells and Main Features

Waste disposal cells at the site are permanent, clay-lined cells with composite clay and rock cap designed to perform for a minimum of 500 years.

Hydrogeology and Climate

The soil deposits at the facility are the Quaternary-age lacustrine lake bed deposits associated with the former Lake Bonneville. These surficial lacustrine deposits generally comprise low-permeability silty clay.

Beneath the facility, the sediments consist predominantly of interbedded silt, sand, and clay with occasional gravel lenses. The depth of the valley fill beneath the facility is unknown; estimates range from 250 to 3,000 ft below ground surface.

The climate at the facility location is semi-arid with an average precipitation of 8.43 in./year and average pan evaporation of 53.3 in./year based on on-site data collected from 1993 to 2018.

The regional groundwater flow direction is toward the Great Salt Lake to the east-northeast. Groundwater recharge to alluvium-filled valleys in the Basin and Range Province occurs primarily through the alluvial fan deposits along the flanks of the adjoining mountains. Because of the low precipitation and high evapotranspiration, direct infiltration of water into shallow aquifers in the valley floors is negligible.

Both a shallow unconfined aquifer and a deep confined aquifer lie below the facility. Isotopic studies conducted to characterize groundwater recharge sources, groundwater age, and groundwater geochemical evolution indicated that the ionic composition of groundwater at the facility was consistent with very slow horizontal flow rates. The groundwater in both aquifers is extremely saline. The salinity of the water is high because of dissolution of evaporite deposits and concentration of salts due to evapotranspiration. Groundwater beneath the facility is classified as a Class IV saline groundwater under the state of Utah Groundwater Quality Protection Regulations standards for total dissolved solids (exceeding 10,000 mg/L) (*Utah Administrative Code* [UAC] R317-6-3, "Ground Water Classes"). Naturally occurring concentrations of many dissolved constituents (e.g., arsenic, selenium, thallium, radium, and uranium) exceed EPA and Utah State drinking water standards (Mayo and Associates, 1999; Bingham Environmental, 1996; Energy*Solutions*, 2014).

Disposal Facility Design

The design and operation of the Energy*Solutions* disposal site provides a long-term disposal solution with a minimal need for active maintenance after closure. Energy*Solutions* uses an above-ground engineered disposal cell. The design of these cells is patterned after DOE and EPA specifications for the Vitro disposal embankment.

The design of the CAW cell is similar to the design of the existing Class A cell, with a larger footprint. The CAW disposal cell occupies approximately 133 ac. The cell is excavated into the native silty clay soil with waste placed above a layer of compacted clayey soils and covered with a layered engineered cover constructed of natural (no man-made) materials. The cover design is engineered to reduce infiltration, prevent erosion, and protect from radionuclide exposure. The landfill design includes both a low-angled top slope and a steeper side slope section of the cover. The layers of the CAW top slope cover consist of the following from bottom to top:

- **Liner**. The cell will be lined with a 0.61 m (2-ft) thick layer of compacted clayey native soil (Unit 4).
- **Waste**. The waste layer will not exceed a final thickness of 23 m (75.3 ft) above the top of the clay bottom liner. The height of waste at the shoulder of the top slope (the contact between the top slope and side slope) will be approximately 11.4 m (37.6 ft).
- **Radon barrier**. The top slope cover design contains an upper radon barrier consisting of 0.3 m (12 in.) of compacted clay with a maximum hydraulic conductivity of 5×10^{-8} cm/sec and a lower radon barrier consisting of 0.3 m (12 in.) of compacted clay with a hydraulic conductivity of 1×10^{-6} cm/sec.
- **Filter zone (lower)**. The 0.15 m (6 in.) of Type B filter material will be placed above the radon barrier in the top slope cover.
- **Sacrificial soil (frost protection layer)**. A 0.3 m (12-in.) layer consisting of a mixture of silty sand and gravel will be placed above the lower filter zone to protect the lower layers of the cover from freeze/thaw effects.
- **Filter zone (upper)**. The 0.15 m (6 in.) of Type A filter material will be placed above the sacrificial soil in the top slope cover. The Type A material-size gradation corresponds to a poorly sorted mixture of coarse sand to coarse gravel and cobble.
- **Rip rap cobbles**. Approximately 0.45 m (18 in.) of Type B rip rap will be placed on the top slopes, above the upper (Type A) filter zone.

The design for the side slope is similar to the top slope, except for the thickness of the waste layer and the material used in the rip rap layer.

- **Waste**. The thickness of waste will range from zero at the edge of the cell to 11.4 m (37.6 ft) at the shoulder, for an average waste height of 5.7 m (18.8 ft) [(0+37.6)/2)].
- **Rip rap cobbles**. Approximately 0.45 m (18 in.) of Type A rip rap will be placed on the side slopes above the Type A filter zone.

Key Regulatory Requirements

The applicable federal agency that regulates disposal of LLRW at the Clive facility is the NRC. The regulations (10 CFR 61, and Utah regulation R313-25-9, "Technical Analyses") indicate the need to evaluate performance with respect to members of the public and inadvertent human intruders.

Energy*Solutions* is permitted by the state of Utah to receive Class A LLW under UAC R313-25, "License Requirements for Land Disposal of Radioactive Waste." The wastes that are received must be classified in accordance with the UAC R313-15-1009, "Classification and Characteristics of Low-Level Radioactive Waste." The classification requirements in UAC R313-15-1009 reflect those outlined in the NRC's waste classification system, 10 CFR 61.55, which divides LLW into classes for disposal – with Class A LLW being the least hazardous and greater-than Class C (GTCC) LLW being the most hazardous. The Clive facility is licensed for disposal of Class A LLW and MLLW and bulk Class A LLW and MLLW in reusable packages with dose rates of <100 mrem/hour at 30 cm (~1 ft).

A determination of the Class of the waste is based upon a comparison against limits in two tables, one for short-lived radionuclides and one for long-lived radionuclides, extracted from 10 CFR 61.55. A detailed projection of waste classes is provided in Section H.6 of Volume II, Appendix H. Calculated results in that appendix show that the percentage of expected LAW from supplemental treatment in a grouted waste form that would be Class A waste range from 83 to 93%, depending on feed vector characteristics and whether a Hanford System Plan representative feed (Scenario SP9 1B) is used or an "Early Start" feed is used (ORP-11242, Rev. 9). The feed vectors represent monthly average concentrations of 46 radionuclides for each month of waste generation. The SP9 1B feed vector is not relevant for purposes of determining classes of waste for the two off-site alternatives analyzed in detail, Grout 4B and Grout 6, as they assume an Early Start feed vector. For alternatives Grout 4B and Grout 6, the percentage of waste form that would be Class A is at the low end of the range above. This is because the concentrations of long-lived radionuclides are higher during this time.

Subpart C of 10 CFR 61 specifies the performance objectives for the near-surface LLW disposal facilities – protection of general population and inadvertent intruders. The near-surface disposal is defined as disposal in or within the upper 30 m (100 ft) of the earth's surface (10 CFR 61.2).

In addition, groundwater protection levels (GWPL) must be adhered to, as outlined in the site's Ground Water Quality Discharge Permit (UWQB, 2010). The GWPLs are numerical standards that are set by Utah Department of Environmental Quality (UDEQ) in the groundwater quality discharge permit (UWQB, 2009). Groundwater in the vicinity of the site is defined as Class IV, saline groundwater (UWQB, 2009), and GWPLs for existing wells were determined by UDEQ according to administrative rules for Class IV saline aquifers. GWPLs were set at the greater of either the Ground Water Quality Standard (GWQS) or the upper boundary of the background concentration.

Waste Acceptance Criteria

The type, form, and quantity of LLRW, NORM, 11e.(2) byproduct material, and mixed waste that can be treated and disposed of at the Clive facility is defined in licenses and permits. The licenses issued to Energy*Solutions* by the Utah Division of Waste Management and Radiation Control applicable to the LLRW and mixed waste are:

- An Agreement State radioactive material license (UT 2300249). This license authorizes Energy*Solutions* to receive Class A LLRW, NORM, and naturally occurring and accelerator-produced radioactive material (NARM) waste.
- A state-issued Part B Permit (EPA ID Number UTD982598898) to treat and dispose of hazardous waste that is also contaminated with LLRW, NORM, or NARM wastes (mixed waste).
- An Agreement State radioactive material license (UT 2300478) for 11e.(2) byproduct material (as defined by the AEA).

In addition to waste acceptance criteria, as low as reasonably achievable (ALARA) criteria are applied to minimize worker exposures. The ALARA criteria are not a license condition but are used as the primary distinction between waste that is acceptable for direct disposal at the Bulk Waste Facility and Containerized Waste Facility. The ALARA criteria define allowable external contact dose rates and loose surface contamination limits for waste managed at the Bulk Waste Facility.

The disposal volume available at Clive is 2,293,665 m^3 (3 million yd^3). Consequently, disposing of all Class A Hanford LAW from supplemental treatment at Clive will take from 8 to 15% of the available disposal volume. Clive does not have a limit on the total activity.

Disposal Performance Evaluation

There are two disposal performance evaluations: (1) Class A West Disposal Cell and (2) a proposed Depleted Uranium Cell. The performance evaluation specifies the dose limits to the general population due to the exposure to the radioactive materials released in groundwater, surface water, air, soil, plants, or animals. Clive is a remote and environmentally inhospitable area for human habitation. Human activity at Clive has historically been very limited, due largely to the lack of potable water or even water suitable for irrigation. None of the exposure pathways at the site are viable as explained below. However, the groundwater pathway was analyzed in great detail to provide evidence that GWPLs in the compliance monitoring well are below the limits outlined in the site's Ground Water Quality Discharge Permit (UWQB, 2010).

For the Class A West Disposal Cell, the performance evaluation determined the following conclusions for the different pathways and the protection of individuals from inadvertent intrusion. Additional details on the performance evaluation, including a more in-depth discussion of the groundwater analysis, are included in Volume II, Appendix G.

- **Air pathway**: The evaluation determined that radon releases will be negligible because the cover design includes a clay radon barrier designed to limit the surface radon flux to less than 20 $pCi/m^2/sec$, resulting in potential radon exposures well within limits.
- **Soil pathway**: The soil pathway entails the exposure of the public to contaminated soil from the facility. Both the location of the facility and closure contribute to low exposures as no contaminated soil material is expected to rise to the ground surface or otherwise be removed from the disposal cell.
- **Surface water pathway**: Due mainly to the natural site characteristics, no radioactive releases are expected through the surface water pathway. The annual precipitation is low and evaporation is high. No permanent surface water bodies are on the site.

- **Plant pathway**: Exposures via the plant uptake pathway are not expected. Insufficient water exists at the site to produce food crops. In addition, saline soils present at the site limit the number and type of plant species that can tolerate such conditions.
- **Burrowing animal pathway**: The design of the facility, including the riprap erosion barrier and the clay radon barrier, is expected to preclude burrowing animals from reaching the waste layers.
- **Groundwater pathway**: The groundwater protection criteria are based on an annual dose of 4 mrem to an individual drinking groundwater. The primary site characteristics prevent public exposures via the groundwater pathway due to very poor groundwater quality at the site, low population density, and relatively slow groundwater flow velocities. No domestic water use occurs within 10 km of the facility. Even though the groundwater is not potable, potential doses to the public from groundwater were calculated and met all applicable limits.
- **Inadvertent intruder**: Intruder protection is promoted by the location and design of the disposal facility. The embankment cover system provides the long-term barrier to inadvertent intrusion, with 1.1 m (3.5) ft of rock layers, 0.61 m (2 ft) of clay, and 0.3 m (1 ft) of noncontaminated native soil as a "temporary cover" above the waste. Further, limiting the waste to Class A has been determined to protect inadvertent intruders.

A separate performance assessment has been performed for the Proposed Depleted Uranium Cell. This analysis is documented in Neptune (2021). The PA is probabilistic and goes beyond the 500 years because depleted uranium reaches peak activity at 2.1 Myr. Even though this analysis was done for a different inventory than the one that will be disposed of at the CAW disposal cell, the analysis provides additional confidence in the performance of the Clive facility.

Other Considerations

The following other considerations are summarized below and discussed in more detail in Volume II, Appendix G:

- **Operating experience**: Energy*Solutions* has over 34 years of experience operating the Clive facility. The NORM waste disposal operations at the Clive facility began in 1988. LLRW disposal operations began in 1991. Mixed waste disposal operations have been conducted since 1992. The Clive facility has received waste from cleanup activities carried out across the country, including projects by the EPA, DOE, DoD, utilities, and other commercial entities. Energy*Solutions* received, treated, and disposed of over 1.5 Mgal of waste shipped in International Organization for Standardization tankers from the DOE Rocky Flats closure project. Energy*Solutions* has disposed of more than 2.4 million m^3 (85 million ft^3) of waste from DOE sites over the last 25 years.
- **Compliance monitoring wells**: A compliance monitoring well network was developed for the CAW embankment that includes 27 wells. The monitoring well network is designed to verify regulatory compliance with the state of Utah GWPLs and to provide early warning of potential releases. A well spacing analysis was performed to provide reasonable assurance that releases from the CAW embankment can and will be detected. The modeling was performed using ^{129}I and ^{99}Tc as the surrogate contaminants. These radionuclides were selected because of their potential presence in CAW embankment Class A waste, their conservative transport characteristics (i.e., relatively mobile), and because of their long half-lives relative to the modeled time period of 500 years.
- **Financial assurance**: Funds for the closure, remediation, and long-term surveillance of the Clive facility are maintained in trust for the benefit of the state of Utah. Furthermore, the state of Utah has established a Perpetual Care Fund with a target initial minimum balance of $100 million at the conclusion of the post-closure monitoring period (i.e., year 101 after site closure).

The Perpetual Care Fund is funded by an annual payment, and earnings are accrued to the fund cash balance. In addition to the estimated costs for decommissioning the Clive facility, the financial surety also covers estimated costs of long-term surveillance of the site, including sampling of groundwater monitoring wells, site inspections and repairs, and other miscellaneous costs.

D.2.3 Waste Control Specialists, LLC Waste Disposal Facility (Andrews, Texas)

WCS is a treatment, storage, and disposal company dealing in radioactive, hazardous, and mixed wastes. Their primary facilities are located on 1,338 ac (540 ha) of land that is 35 mi (56 km) west of Andrews, Texas, and 5 mi (8 km) east of Eunice, New Mexico.

Transportation and Disposal

WCS treatment capabilities include dewatering, stabilization, and repackaging. Their transportation capabilities include ownership of three Type B shipping casks and two Type A shipping containers. WCS has three separate disposal facilities for radioactive wastes, including (1) a facility for disposal of commercial radioactive wastes from the Texas Low-Level Radioactive Waste Disposal Compact, and radioactive wastes imported from 36 other states into the Texas Compact; (2) a facility for disposal of 11e(2) byproduct material; and (3) the Federal Waste Disposal Facility (FWF).

Figure D-4 is an aerial view of the disposal facilities for radioactive wastes at WCS. The remainder of this subsection focuses exclusively on the FWF, which was designed, licensed, and constructed for federal waste disposal, including all wastes from DOE.

Figure D-4. Clive Waste Disposal Facility

WCS is equipped to receive wastes by truck and by rail. For rail, a receiving building straddles the railhead and a WCS-owned locomotive brings wastes onsite from nearby Eunice, New Mexico.

The area surrounding the WCS facilities is sparsely populated and (on average) receives less than 400 mm (16 in.) of rainfall per year. Based on an extensive site investigation program, including over 500 wells and core samples, the geology and hydrology of the WCS site is well understood.

Hydrogeology

The WCS facilities are located over a geologic feature referred to as the “buried red ridge”. This buried red ridge is part of another geologic layer that consists of a series of fluvial and lacustrine mudstones, siltstones, sandstones, and silty dolomite deposits that are over 1,000 ft thick beneath the WCS site. The buried red ridge is encountered at depths ranging from about 8 to 80 ft beneath the WCS facilities.

An Ogallala Formation exists to the northeast of the site and extends above the buried red ridge, it is not water bearing in the WCS area. The site is completely isolated from the part of Ogallala formation that is saturated to the north and east of the buried red ridge and from the regional Ogallala Formation in the Southern High Plains. The WCS facilities are not located over a drinking water aquifer or adjacent to any underground drinking water supply.

In the Dockum Group beneath the WCS facilities, there are transmissive zones in the sandstones/ siltstones. The uppermost, laterally-continuous and continuously-saturated transmissive zone is a 10- to 35-ft thick sandstone/siltstone at a depth of about 225 ft. This unit, referred to as the 225-ft zone, has a very low permeability of approximately 10^{-8} cm/sec. WCS has monitoring wells screened in the 225-ft zone in all three landfill areas. Because of the low transmissivity and salinity, the 225-ft zone is not classified as a drinking water aquifer. The groundwater pathway was excluded from the site performance assessment.

Disposal Facility Design

Wastes are emplaced ~8 to 37 m (25 to 120 ft) below the land surface in the FWF disposal cell that includes a 7-ft (2 m) thick multi-barrier liner. When constructed, the multi-barrier cap over the cell will be a minimum of 25 ft (~8 m) thick and will be completed at-grade. Higher-activity Class B and C LLW and MLLW are disposed of in modular concrete canisters (MCC) inside the disposal cell. The MCCs are 150 mm (6-in) thick steel-reinforced concrete containers. The natural site characteristics and barriers (e.g., no drinking water aquifer and thick red clay beds) and the engineered barriers (e.g., 2-m thick multi-barrier liner and MCCs) work together to give WCS one of the most robust multi-barrier designs of any Agreement State-licensed LLW disposal facility in the United States.

WCS uses two standard types of MCC: (1) cylindrical: 1.8 m (6 ft) and (2) rectangular: 2.9 m long × 2.3 m wide × 2.8 m high (9 ft-6 in. long × 7 ft-8 in. wide × 9 ft-2 in. high) (internal). Typically, Class B and C LLW, inside a U.S. Department of Transportation (DOT) shipping container, is placed in an MCC, any void space is grouted and the concrete lid is placed on top. A waste that is disposed of in an MCC is categorized by WCS as a *containerized waste*. In contrast, *bulk wastes* may be shipped in reusable DOT shipping containers, the wastes are not disposed of in the DOT shipping container and the waste is not placed in an MCC. Bulk waste is acceptable for disposal in the FWF, if the waste is Class A and has a dose rate of <100 mrem at 30 cm (~1 ft). Bulk waste is sometimes disposed of in an MCC (e.g., if the dose rate of the bulk waste is >100 mrem at 30 cm [~1 ft]). Figure D-5 shows the wastes being loaded into rectangular MCCs inside a disposal cell with components of the multi-barrier liner visible in the background.

Figure D-5. Wastes Being Loaded into Modular Concrete Canisters at the Waste Control Specialists Disposal Cell

As noted in Section D.1, this study assumes that the waste forms will be shipped and disposed of using 8.4-m^3 "soft-side" shipping containers. If the waste is determined to require containerization, as noted above, two soft-side containers with a capacity of 8.4 m^3 each (11 yd^3) each will fit in a standard rectangular MCC (allowing ~ 50 mm (2 in.) extra on all four sides and 50 mm (2 in.) extra on top).

Key Regulatory Requirements

Texas is an NRC Agreement State, and the Texas Commission on Environmental Quality (TCEQ) is responsible for licensing and inspecting the WCS radioactive and mixed waste disposal facilities. For licensing the FWF, TCEQ used their state regulations that are equivalent to the 10 CFR 61 licensing requirements. After a detailed multi-year licensing process in 2009, TCEQ issued a Radioactive Materials License to WCS to dispose of LLW (TCEQ, 2009).

The following are key FWF regulatory considerations:

- FWF is licensed to accept Class A, B, and C LLW and Class A, B, and C MLLW for disposal.
- Before disposal, all waste must meet LDR requirements in 40 CFR 268 (or state equivalent LDR requirements).
- The FWF is licensed for up to ~736,000 m^3 (26,000,000 ft^3) and 5,600,000 total curies of wastes. The FWF is designed to be built in 11 phases. Only the first of the 11 phases has been completed.

The term of the current license is through September 2024, with provision for 10-year renewals thereafter. The state of Texas takes ownership of LLW disposed of in the Compact Disposal Facility; DOE has signed an agreement to take ownership of the FWF after its closure. In post-closure, DOE will be responsible for the waste forms disposed of in the FWF.

In addition to the license issued by the TCEQ, WCS maintains other permits and licenses, which are listed on their website (WCS, 2022).

Waste Acceptance Criteria

The waste acceptance criteria for the FWF are included as an amendment to the TCEQ license for the FWF; these criteria are detailed in the WCS *Federal Waste Disposal Facility (FWF) Generator Handbook* (WCS, 2015).

The waste acceptance criteria for the FWF include limits on free liquids (<1% of the volume of containerized waste), maximum void space limits, transportation requirements, and prohibited waste types. Prohibited wastes include high-level radioactive waste; waste capable of generating toxic gases (excluding radioactive gases); and waste readily capable of detonation, of explosive decomposition, reaction at normal pressures and temperatures, or of explosive reaction with water.

Some of the general packaging requirements are:

- Each container can only contain one approved profiled (characterized) waste stream
- Packages should weigh 10,000 lb (4,545 kg) or less, unless special arrangements have been made
- All containers transported on public roads to WCS are required to meet the applicable DOT regulations
- Except for bulk wastes and large components, waste packages must fit in an MCC.

The wastes disposed of at WCS must comply with the LDRs detailed in 40 CFR 268. The FWF is licensed for disposal of Class A, Class B, and Class C (as defined in 30 TAC 336.362, "Appendix E. Classification and Characteristics of Low-Level Radioactive Waste") LLW and MLLW, and bulk Class A LLW and MLLW in reusable packages with dose rates <100 mrem/hr at 30 cm (~1 in.). The percentages of waste that would be Class A, Class B, or Class C are expected to be the same, as discussed in Section D.2.2, for Clive (Energy*Solutions*). In all grout cases, the Class B and C waste forms are produced only during the first 7 years of operations for alternatives using the Hanford SP9 1B supplemental LAW characteristics or during the first 18 years of operations (Early Start).

Disposal Performance Evaluation

The WCS disposal PA (WCS, 2011) examines site features such as geology, surface water and groundwater, potential future weather changes, residential and intrusion scenarios, and possible future uses of the land. The WCS PA meets all state of Texas requirements during the performance period of 10,000 years after site closure.

When considering transport in the porous-medium water phase, inventory radionuclides are assumed to be uniformly distributed and available for leaching by a conservative partition coefficient (K_d) exchange leaching model. This leaching model conservatively assumes that all the radionuclides are available for contact with water and migration. No credit is taken for waste containers, concrete canisters, or improved waste forms such as activated metals or solidified or encapsulated wastes. The entire radionuclide inventory is immediately available for release and transport (WCS, 2007, Appendix 8.0-6).

Radionuclide pathways analyzed in the PA include the following:

- **Surface water pathway** – The surface water pathway was determined to be irrelevant for contaminant release due to a number of factors, including the semi-arid nature of the location where the loss of water by evapotranspiration exceeds precipitation, the absence of streams on or near the site, and the good drainage of site soils.
- **Air pathway** – The air pathway for the WCS Site Model is largely driven by gas emanation through the finished cover. The air pathway is the main risk driver for longer lived, highly mobile radionuclides such as ^{129}I or ^{14}C.
- **Groundwater pathway** – Although there are no potable water sources in the area near the WCS facility and very low vertical velocity beneath the WCS site, the groundwater pathway was analyzed in detail and potential impacts were quantified. The conclusion of these analyses was that there is no realistic groundwater pathway at WCS (WCS, 2011).
- **Other analyzed exposure pathways** – Intruder analyses were also considered, including an intruder driller and an intruder resident. Additionally, an adjacent resident was also evaluated, with the gaseous diffusion and corresponding inhalation dose determined to be the dominant exposure pathway.

Other Considerations

Other considerations include:

- **Waste ownership** – Upon receipt, Texas Compact LLW waste ownership is transferred to the state of Texas and federal LLW is transferred to DOE after post-closure of the FWF.
- **Retrievability** – The Class B and C waste will be disposed of in MCCs. MCC placement allows for waste retrievability via global positioning system technology.
- **Monitoring well network** – Over 400 monitoring wells are measured quarterly, many of which are dry. Approximately 150 monitoring wells are laboratory sampled semi-annually if there is enough water.

D.3 TRANSPORTATION

This section primarily focuses on transportation to the off-site disposal facilities: Energy*Solutions* in Clive, Utah, and WCS near Andrews, Texas. Transportation of LAW to the IDF would follow the same essential requirements as the vitrified waste from the WTP LAW facility. For disposal at IDF, waste forms considered in the analysis included vitrified waste, grouted waste, and a FBSR waste form. For off-site disposal, only waste forms from grouting or FBSR alternatives were considered. This is because current planning, permits, and existing and planned infrastructure support disposal of a vitrified waste form in the IDF and there was not perceived to be any advantage to disposing this waste form offsite.

Per DOE O 460.1D, *Hazardous Materials Packaging and Transportation Safety*, DOE has broad authority under the AEA, as amended, to regulate activities involving radioactive materials that are undertaken by the DOE or on its behalf, including the transportation of radioactive materials. In most cases that do not involve national security or other critical interests, DOE uses commercial carriers that undertake its shipments subject to regulation by DOT and NRC as appropriate. However, DOE exercises

its AEA authority to regulate certain DOE shipments, including shipments by government employees and on-site transfers. In all cases, DOE's packaging and transportation activities must be conducted in a manner that achieves an equivalent level of safety to that required by DOT and NRC for comparable commercial shipments. Requirements are specified under DOE's directive system through DOE Orders and Manuals:

- DOE O 460.1D establishes safety requirements for the proper packaging and transportation of off-site shipments and on-site transfers of hazardous materials, including radioactive materials.
- DOE O 460.2A, *Departmental Materials Transportation and Packaging Management*, invokes DOT requirements or documented requirements providing equivalent safety for on-site shipments.
- DOE M 460.2-1A, *Radioactive Material Transportation Practices Manual,* establishes a set of standard transportation practices for DOE organizations to use in planning and executing off-site shipments of radioactive materials (e.g., radioactive waste), including a framework for interacting with state, Tribal, and local authorities; other Federal agencies; and transportation contractors and carriers regarding DOE radioactive material shipments.

The programs that will be needed to transport grout waste forms from the Hanford Site to either WCS or Energy*Solutions* are identified below:

- General evaluation assumptions and approach
- Key regulatory considerations for packaging and transportation
- Package requirements
- Transportation routes and schedules
- Transportation and disposal costs
- Nonmonetary considerations related to transport
- Risks.

D.3.1 General Evaluation Assumptions and Approach

This study assumes the current status of infrastructure (e.g., railroads, the current regulatory requirements for shipping, and the current shipping and packaging technologies). Basing the analyses on current conditions removes speculation about future conditions while allowing an even-handed comparison of disposal of grout and FBSR waste forms at the off-site disposal facilities. Based on the existing physical capacities of the Clive and WCS facilities, all Class A grout or FBSR LAW waste forms can be disposed of either at Clive or WCS. Based on the existing WCS facility physical capacity, all Class B and C grout waste forms can be disposed of at the WCS disposal facility, in addition to all Class A waste from supplemental treatment.

The use of supplemental LAW feed vectors is introduced in Section D.2.2 for the purpose of predicting the amounts of Class A wastes. A Hanford SP9 1B scenario feed vector is used in the FBSR 1B, Grout 1B, and Grout 2B alternatives. The total liquid volume in this feed vector is 56.2 Mgal. The waste generation period is from January 2034 to February 2076. For off-site transportation purposes, alternatives FBSR 1B, Grout 1B, and Grout 2B were not among the selected alternatives for detailed evaluation.

The Early Start feed vector is used in alternatives Grout 4B and Grout 6, which were evaluated in detail. The total liquid volume in this feed vector is 95.2 Mgal. The waste generation period for this feed vector is from March 2028 to November 2064.

Several figures and tables in Section D.3 were extracted from Volume II, Appendix H, which has a detailed discussion of transportation considerations, including costs for the alternatives entailing off-site disposal. Appendix H also evaluated considerations with both the SP9 1B and Early Start feed vectors. Where tables or figures from that appendix included both feed vectors, they were retained in this

appendix for consistency purposes; however, as noted above, the SP9 1B feed vector does not apply to the two alternatives evaluated in detail that entail off-site disposal.

D.3.2 Key Transportation Regulatory Considerations

DOE incorporates appropriate requirements from the NRC concerning the regulation of the packaging for the transport of radioactive materials, and the DOT coordinates with the NRC to set rules for the packaging. The DOT also works with the NRC and affected states to regulate their transport.

10 CFR 71 Packaging and Transportation of Radioactive Materials

10 CFR 71, "Packaging and Transportation of Radioactive Material," defines the packaging and transportation performance criteria to ensure the safe transport of radioactive materials under normal and hypothetical accident conditions. This NRC regulation uses a graded approach in setting packaging criteria to protect public health depending upon activity and hazard of the material. It establishes three levels of packaging depending upon limits listed in the regulation: (1) industrial packaging (IP), (2) Type A packages, and (3) Type B packages. Working with NRC, the DOT has established categories for radionuclide concentrations that determine the type of packaging to be used. These categories use the term Low-Specific Activity (LSA), with different LSA levels requiring different levels of packaging.

All packages for shipping radioactive material (IP, Type A, or Type B) must be designed and prepared so that under conditions normally incident to transportation, the radiation level does not exceed 2 mSv/hour (200 mrem/hour) at any point on the external surface of the package, and a limit for all packages in a shipment.

The supplemental LAW waste forms meet all the requirements of LSA-II materials and can be transported in industrial package (IP)-2 or IP-3 packaging (Volume II, Appendix H, Section H.5). Shipping in a Type A or/and Type B shipping cask is not expected to be necessary. Additional details on the proposed packages for liquid and solid waste forms are provided in Section H.7.1 of Volume II, Appendix H. A description of the process for determining the specific activity and the type of packaging are in Section H.5 of Volume II, Appendix H.

That section also compares the expected activities of the supplemental LAW feed vectors to the limits for LSA-II and concludes that pretreated supplemental LAW liquids, treated grout waste forms, and FBSR waste forms meet the LSA-II limit for liquids and solids in all off-site disposal alternatives with considerable margin. The LSA requirements for liquids also require determination of total activity of a shipment or conveyance, considering the total number of tankers in a shipment. LSA materials must be nonfissile or be exempt under 10 CFR 71.15, "Exemption from Classification as Fissile Material." Although six exemption criteria are provided, the only criterion applicable for supplemental LAW liquids is the total mass of fissile isotopes ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu must be 2 g or less in a package with radioactive liquids.

Figure D-6 depicts the number of liquid container volumes necessary to remain below the fissile limits and shows that the bulk of shipments can be in 4,000-gal containers or less.

The monthly number of containers with liquids per conveyance was calculated using LSA limits as discussed in Volume II, Appendix H, Section H.5. Figure D-7 shows the monthly number of containers per conveyance for the SP9 1B and Early Start feed vectors.

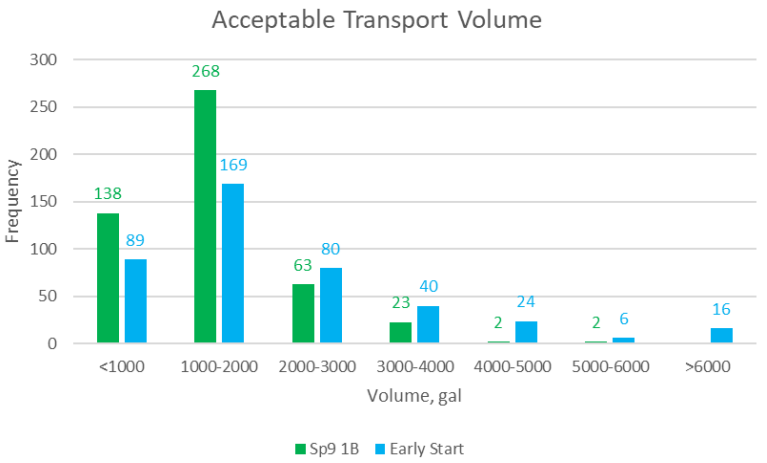


Figure D-6. Liquid Volumes Meeting Nonfissile Exempt for Liquids

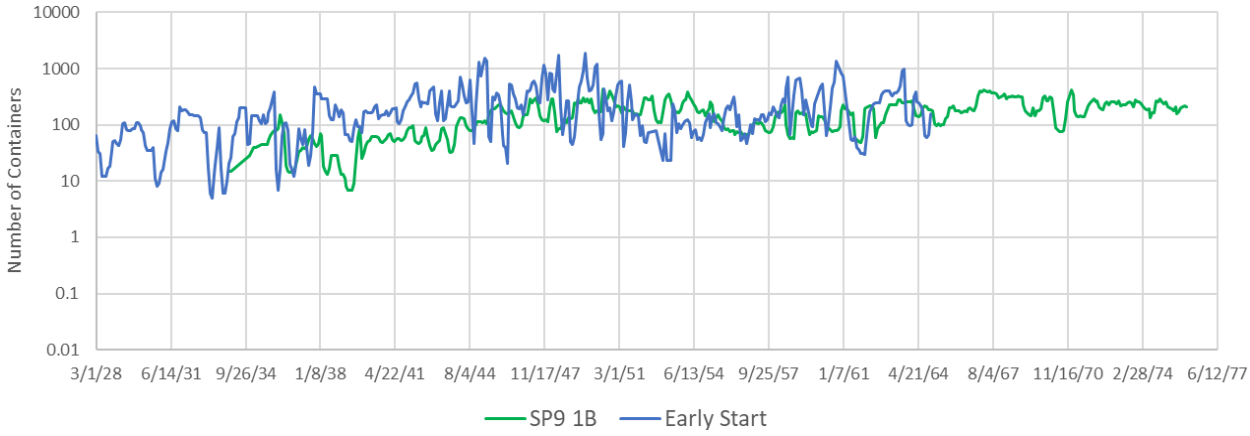


Figure D-7. Number of Containers with Liquids per Conveyance

Figure D-8 presents the same information in the form of a histogram. Based on Figure D-7, 95% (SP9 1B) and 92% (Early Start) of trains can carry 25 containers with liquids (or more) to meet LSA requirements.

The liquid waste treatment capacity, whether at an independent vendor facility, or at Clive or WCS, should be sufficient to process the corresponding annual volumes. The existing licenses at Clive and WCS would need to be amended if larger volumes need to be treated.

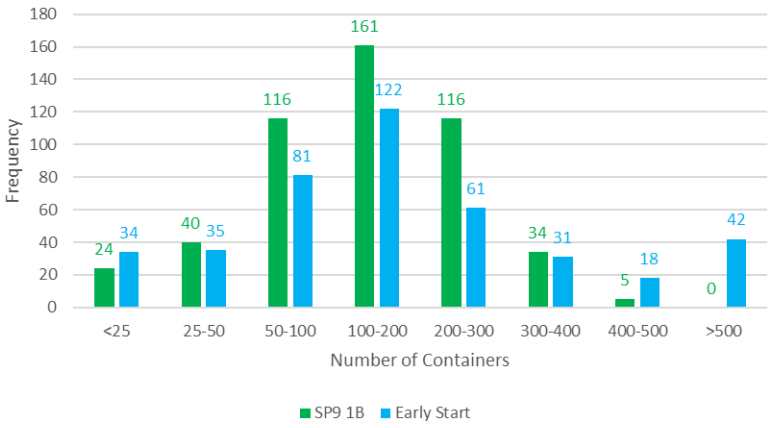


Figure D-8. Number of Containers per Conveyance per Month

External Dose Rates

10 CFR 71.47, "External Radiation Standards for all Packages," provides requirements for external doses for transportation under LSA packaging:

- Each package of radioactive materials must be designed and prepared for shipment so that under conditions normally incident to transportation, the radiation level does not exceed 2 mSv/h (200 mrem/h) at any point on the external surface of the package, and the highest dose rate 1 m from the source does not exceed 0.1 mSv/h (10 mrem/hr).
- A package that exceeds the radiation level limits above must be transported by exclusive use shipment only, and meet other requirements.

(These are discussed in more detail in Volume II, Appendix H, Section H.5.)

Total monthly activities of the liquid waste form for the SP9 1B and Early Start feed vectors are higher than the total monthly activities of the grout waste form because the radionuclide concentrations are diluted when a grout waste form is generated. Consequently, if liquids meet the dose requirements, the grout waste form will also meet them. In addition to the lower activities, grout is self-shielding, which leads to further lower doses.

Calculations performed using MicroShield for an ISO tank containing radioactive liquids are described in Volume II, Appendix H, Section H.5.3. As shown in Figure D-9, the calculations demonstrate that expected maximum external dose rates from a 5,000-gal ISO tank (conservatively used, though 4,000-gal ISO tanks would be proposed) are below the limits above for the Early Start feed vector.

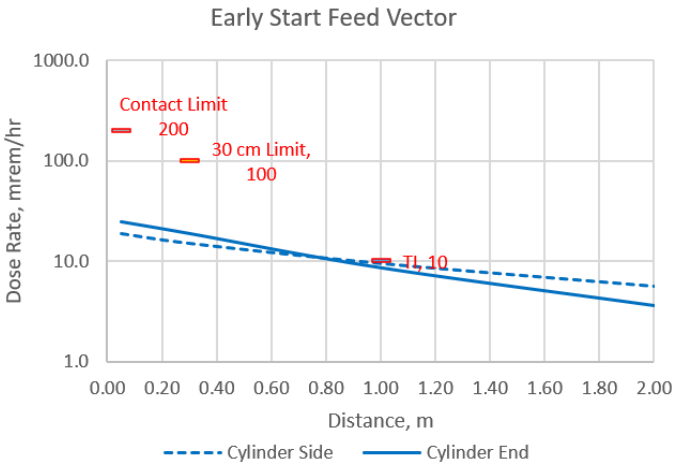


Figure D-9. Maximum External Dose Rates from a 5,000-Gallon ISO Tank with Early Start Feed Vector Liquids

49 CFR 171 – 173 Hazardous Materials Regulations

49 CFR 171–173 address many facets of the transport of radioactive materials, which are a subset of DOT's broader definition of hazardous materials. Each licensee who transports licensed material on public highways or who delivers licensed material to a carrier for transport must comply with the applicable requirements of the DOT regulations in 49 CFR, "Transportation." Some of the activities regulated by 49 CFR 171–173 include:

- Packaging: 49 CFR 173, Subparts A, B, and I
- Marking and labeling: 49 CFR 172, Subpart D; and Sections 172.400 through 172.407 and Sections 172.436 through 172.441 of Subpart E
- Placarding: 49 CFR 172, Subpart F, especially Sections 172.500 through 172.519 and 172.556; and appendices B and C
- Accident reporting: 49 CFR 171, Sections 171.15 and 171.16
- Shipping papers and emergency information: 49 CFR 172, Subparts C and G

- Hazardous material employee training: 49 CFR 172, Subpart H
- Security plans: 49 CFR 172, Subpart I.

The DOT regulations also define "contamination" as the presence of a radioactive substance on a surface in quantities in excess of 0.4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters or 0.04 Bq/cm^2 for all other alpha emitters, while also considering whether the contamination is fixed or non-fixed.

To ensure the appropriate scoping and costing, this study relies on analogous costs from other programs, where DOE has shipped radioactive wastes for disposal (e.g., shipping contaminated soils by rail for disposal). In this way, the scope and cost of meeting the above requirements are captured without summarizing the large number of safety requirements found in 49 CFR 171–173 for shipping radioactive materials.

Other Regulatory Considerations

As noted above, DOE has a set of directives that apply to on-site and off-site transportation. These are not further discussed here.

Actual implementation of a large-scale, off-site disposal program, with the associated transportation program, such as outlined in this appendix (and Volume II, Appendix H), requires additional *National Environmental Policy Act* (NEPA) review.

D.3.3 Off-Site Transportation

Proposed Packaging

DOT requires that LSA materials be transported in packages meeting Type IP-1, Type IP-2, or Type IP-3 packaging criteria (49 CFR 173.411, "Industrial Packages"). 49 CFR 173.427 defines packaging requirements for all types of LSA materials, including the following requirements for LSA-II:

- LSA-II solid materials must be shipped in packages meeting Type IP-2 criteria for both "exclusive" and "non-exclusive" use shipments
- LSA-II liquids must be shipped in packages meeting Type IP-2 criteria for "exclusive" and IP-3 criteria for "non-exclusive" use shipments.

Type IP-2 criteria in turn must meet the general design requirements of 49 CFR 173.410, and when subjected to the tests specified in 49 CFR 173.465(c) (free drop test) and (d) (stacking test) must prevent the (1) loss or dispersal of the radioactive contents, and (2) a significant increase in the radiation levels.

One of the tests, the stacking test, requires that Type IP-2 packages must be able to sustain a compressive load equal to five times the maximum weight of the package for 24 hours without the loss or dispersal of the radioactive contents.

If the supplemental LAW liquids are converted to grout at a separate vendor facility, the grout will have to be transported to Clive and/or WCS for disposal. The IP-2 package proposed for transporting grout and FBSR waste forms is a 8.4 m^3 (11 yd^3) soft-side container. The dimensions of each container will be 2.79 m long × 2.23 m wide × 1.35 m high (110 in. long × 88 in. wide × 53 in. high). To facilitate handling and to provide a rigid form for filling the soft-side containers with grout, the IP-2 soft side containers) can be placed in shipping boxes that can be disassembled. The waste form would remain in the soft-side container and be emplaced as bulk waste if Class A at Clive and/or WCS or in a modular concrete canister (MCC) at WCS if Class B or C.

Two 8.4-m^3 bags will fit into one MMC. Figure D-10 shows an example of a large soft-side container that can be used to ship LSA materials. Conceptually, the shipping box might look like the one shown in Figure D-11, but lighter weight and with a shallower lid.

Source: PacTec, Inc. literature.

Figure D-10. Example of Soft Side Container for Shipping Low-Specific Activity Materials

D.3.4 Transportation Campaign Schedule

Unit trains will likely be used for transport of supplemental LAW. A unit train, also called a block train, is a train in which all cars carry the same commodity and are shipped from the same origin to the same destination, without being split up or stored en route. Unit trains can transport more than 90 rail cars of one type of freight in one car type for one destination, allowing rail cars to bypass intermediary rail yards and run directly from the origin to destination.

Source: Container Technologies Industries, LLC literature.

Figure D-11. Example of a Shipping Box Used for Solid Waste Transport

Liquid Waste Transport

As discussed in Volume II, Appendix H, Section H.5, the volume of liquid waste that can be transported per month is restricted by the acceptable volume that meets the LSA nonfissile material exemption. This volume varies from month to month and exceeds 4,000 gal only in a few months (see Figure D-6). Consequently, a 4,000-gal ISO container was recommended. This information can be used to calculate the number of trains per month that are needed to transport liquids by rail. The transport by a trailer option is only limited by the volume of liquids per container because only one container is transported in a single conveyance.

The number of trains per month was calculated from the monthly feed vector liquid volume, acceptable container volume meeting nonfissile material classification, and the number of containers per conveyance meeting fissile limits. Note that if the number of containers per train meeting fissile limits was greater than 50, then 50 containers per train was assumed as a realistic number of containers in a dedicated train. Figure D-12 shows the monthly number of trains for the SP9 1B and Early Start feed vectors.

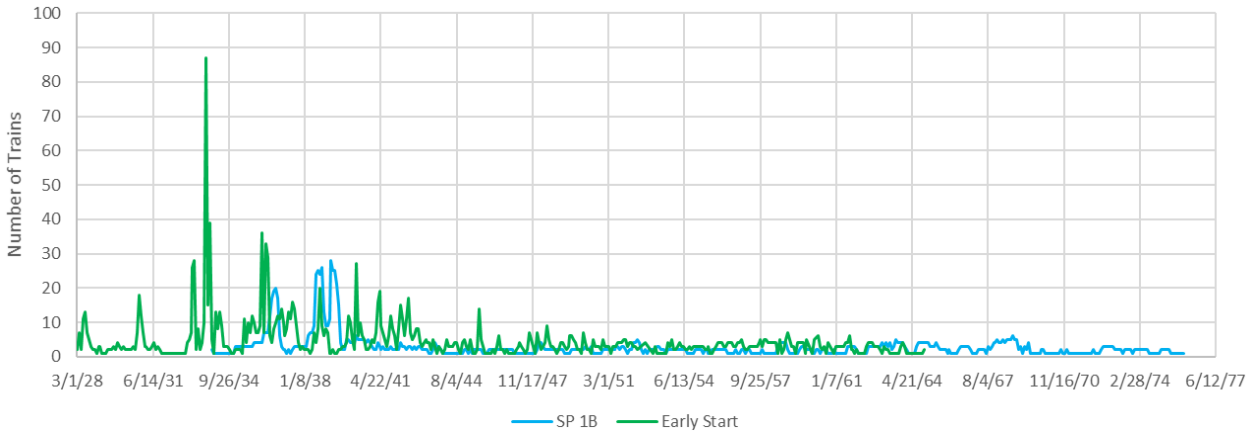


Figure D-12. Number of Trains per Month Required to Transport the Monthly Liquid Volumes

Figure D-13 presents the same information in a histogram. Based on the data presented in Figure D-13, in 79% (Early Start) of the cases, less than five trains per month will be required to transport the liquids. In 21% (Early Start) more cases, five trains or more per month will be required.

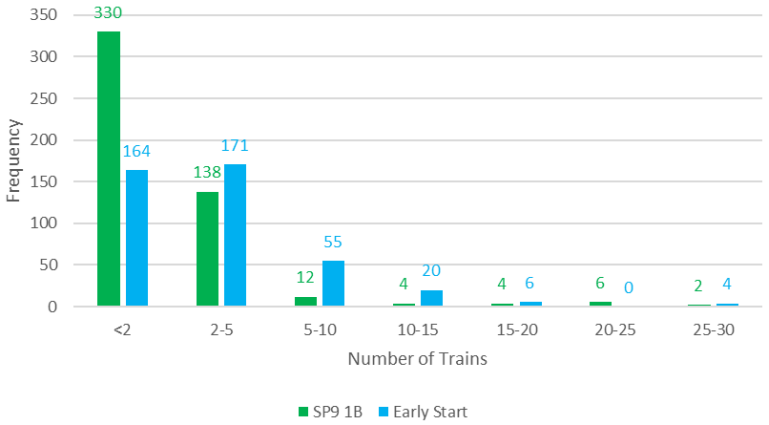


Figure D-13. Number of Trains per Months Histogram

The number of gondolas per month required to transport the generated mass of grout was calculated from the monthly mass of grout generated from the Early Start liquid feed vector assuming six soft-sided bags of grout. Figure D-14 shows the statistics of the calculated number of gondolas in these cases (number of FBSR gondolas are also shown). The number of gondolas per month varies from 1 to 120 for the grout Early Start feed vector. Consequently, only one train per month would be required for grout, with the exception of a few months in grout Early Start. Details of this analysis are in Section H.7.2 of Volume II, Appendix H.

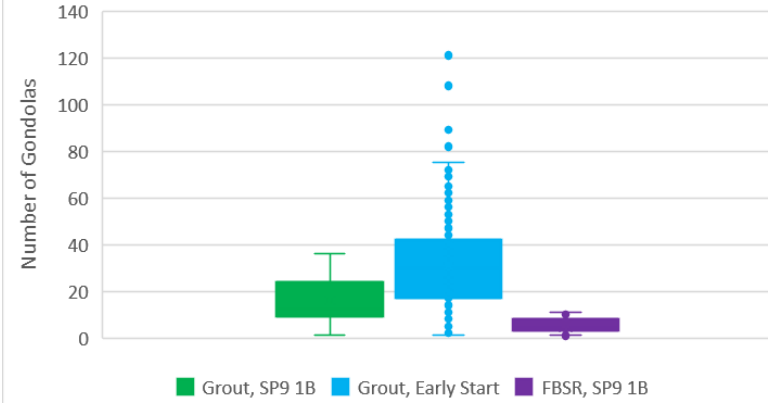


Figure D-14. Number of Gondola per Month Required to Transport Grout or Fluidized Bed Steam Reforming Waste Forms Offsite

D.3.5 Transportation Routes

Figure D-15 is a map of possible rail routes from the Hanford Site to WCS and Clive. The rail routes shown in Figure D-15 were generated with WebTRAGIS, the Oak Ridge National Laboratory routing tool, assuming a dedicated train. The route to WCS ends at the Eunice, New Mexico, rail node. WCS will send their locomotive the short distance to Eunice, New Mexico, to bring the railcars to their facilities in Texas. The route to Clive ends at the Clive facility.

Using the default parameters for route selection in WebTRAGIS yields the route through Oregon, northern California, and Nevada for shipments from Hanford to Clive. When shipments are made, the shipping company and the railroads determine the actual route to use based on many considerations. One possible alternate route is shown through Idaho and Montana in Figure D-16. This route is 1,481 mi, which is slightly longer than the default route (1,213 mi). The analyses presented here are based on using the default WebTRAGIS route. The results based on the alternative route would be similar due to small variations in the route distance and population along the route. Similar alternate routes can also be identified for WCS.

Figure D-15. Rail Routes from Hanford to Waste Control Specialists (Texas) and Clive (Utah)

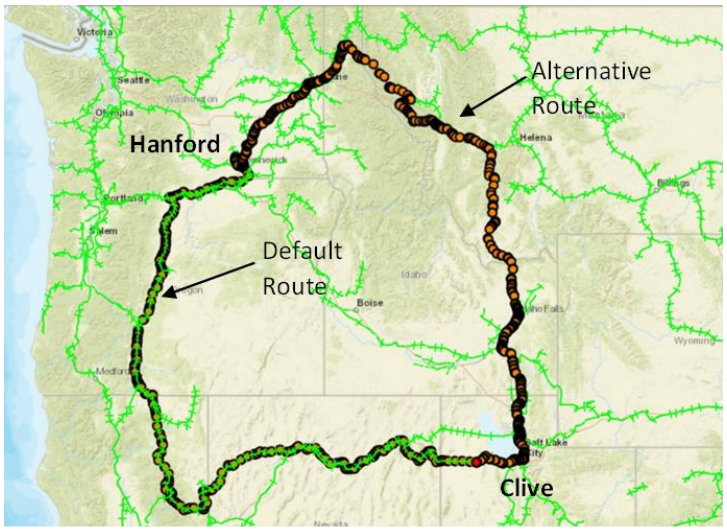


Figure D-16. Default and Alternative WebTRAGIS Routes from the Hanford Site to Clive, Utah

Table D-2 and Table D-3 summarize the route data for the default routes. Table D-4 provides a comparison of the two WebTRAGIS default routes.

Table D-2. Route to Waste Control Specialists (Texas) Waste Disposal Facility Summary

State	Rural Population per mi²	Rural Distance mi	Suburban Population per mi²	Suburban Distance mi	Urban Population per mi²	Urban Distance mi
Colorado	24.6	325.3	1,228.7	100.86	5,336.1	17
Idaho	56.1	63.4	617.9	18.35	0	0
Montana	24.8	562.49	910.8	87.53	5,778.6	7.05
Nebraska	8.9	157.85	809.5	11.01	0	0
New Mexico	9.1	29.77	468.3	2.62	0	0
Oklahoma	21	41.82	280.6	0.99	0	0
South Dakota	13	47.8	253.4	1.09	0	0
Texas	20.4	495.28	976.7	110.66	4,414.3	7.01
Washington	22.6	130.86	1,429.2	48.41	4,674	6.32
Wyoming	15.8	209.55	1,142.9	19.43	3,462	0.54
Total	**21.83**	**2,064.12**	**1,060.37**	**400.95**	**5,110.92**	**37.92**

Table D-3. Route to Clive Disposal Facility (Utah) Summary

State	Rural Population per mi²	Rural Distance mi	Suburban Population per mi²	Suburban Distance mi	Urban Population per mi²	Urban Distance mi
California	10.6	266.71	411.4	7.86	0	0
Nevada	8.7	410.28	784.5	14.5	3,988	1.13
Oregon	21.7	275.71	756.7	40.28	4,968.1	3.57
Utah	2.4	48.06	997	1.13	0	0
Washington	10.7	118.99	1462.5	24.07	3,996.9	1.2
Average/Total	**12.30**	**1,119.75**	**926.89**	**87.84**	**4,582.85**	**5.90**

Table D-4. Route Comparison

Route Parameter	Route to WCS (Texas)	Route to Clive (Utah)
Total population, persons	1,779,152	341,089
Total distance, mi	2,502.99	1,213.49
Average speed, mi/hr	36	23
Number of states crossed	10	5
Number of rail companies	2	1
Number of large cities	5	3
Max population density, persons/mi²	5,778.6	4,968.1
Average rural population density, persons/mi²	21.8	12.3
Average suburban population density, persons/mi²	1,060	927
Average urban population density, persons/mi²	5,111	4,583
Total rural distance, mi	2,064.12	1,119.75
Total suburban distance, mi	400.95	87.84
Total urban distance, mi	37.92	5.9

Section H.7.3 of Volume II, Appendix H provides an analysis of relative population doses from the projected shipments to both sites. The relative population doses (person-rem) per shipping of one soft-side container are 1.16E-05 (route to WCS) and 3.7E-06 (route to Clive). The difference is due to the larger distance to WCS and higher population densities along the route.

D.3.6 Costs

The off-site disposal costs include transportation and disposal costs. When the liquid feed is converted to grout at an off-site facility, there is also a cost of producing the grouted waste form. The total cost will depend on the split of the Class A waste between Clive and WCS. Total costs were calculated for no split cases (all Class A goes to Clive or to WCS) and for 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 fractions of Class A waste going to Clive.

Rail shipping rates are confidential and there are no "look-up tables" to assess the shipping costs. The rates provided by Perma-Fix Northwest, Inc. (Perma-Fix) for shipment to WCS were used, based on numerous prior rail shipments made by Perma-Fix. The rates are $14,000 per loaded gondola and $5,000 for return of the empty gondola. Because the distance to Clive is about half the distance to WCS, the cost of shipping a loaded gondola to Clive is assumed to be half the cost of shipping a loaded gondola to WCS. The cost of the return shipment of an empty gondola is assumed to be the same. The costs of transporting an ISO container is $3,720 (WCS) and $1,860 (Clive). The costs of transporting an empty ISO container either to WCS or to Clive was assumed to be $1,328 empty, based on the same cost ratio as for the loaded-to-empty gondola transportation cost ratio for WCS.

The disposal cost of the bulk Class A waste at Clive is $886.99/yd^3 (Dempsey, 2022) or $1,160.14/m^3. The disposal cost of the bulk Class A waste and Class B and C waste at WCS are $1,460/m^3 and $7,830/m^3, respectively (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*). These costs were used in the calculations of the disposal costs.

The cost of grouting the waste varies depending on where the waste is grouted.

- The cost of off-site grout generation provided by Perma-Fix is $40/gal (Grondin, 2022). For the purpose of the cost estimate, an off-site vendor was assumed to offer grout generation at a similar cost. This cost was used as the rationale for setting the maximum grout generation cost to $45/gal of liquid treated.
- The cost of converting liquid into Class A grout and disposal of grout at Clive is $37.68/gal (Energy*Solutions*, 2019). Converting the disposal costs on a per cubic yard basis to a cost per gallon, the cost of grouting is estimated to be $30/gal.
- Finally, the minimum expected cost of grout generation, based upon a contract for grouting large volumes of LAW on the Hanford Site, is $20/gal (GAO-17-306, *Opportunities Exist to Reduce Risks and Costs by Evaluating Different Waste Treatment Approaches at Hanford*).

Consequently, the calculations were performed assuming $20, $30, and $45/gal of grout generation.

The results of the cost calculations are summarized in Table D-5 and Table D-6 and are plotted on the following pages in Figure D-17 through Figure D-20. In these calculations, the liquid feed is assumed to be converted to grout at a vendor facility and then transported to Clive or/and WCS for disposal. In addition to the total costs, the percent of the annual budget is also calculated, assuming a benchmark annual budget of $450 million dedicated to the supplemental treatment of LAW. The total cost variation from the case when all Class A waste is disposed of at Clive, compared to the case when all Class A waste is disposed of at WCS, ranges from 3.8 to 7.9%. The total cost variation from the case when 50% of Class A waste is disposed of at Clive, compared to the case when all Class A waste is disposed of at WCS, ranges from 2.0 to 5.0%.

Consequently, cost is not a significant differentiator, as discussed below where the total costs include grouting costs, transportation costs, and disposal costs. The case in which off-site disposal only occurs until 2040 corresponds to alternative Grout 6 evaluated in this study.

- For the Early Start feed vector liquid converted to grout at an off-site vendor facility and then transported to Clive and/or to WCS for disposal, the total cost ranges from $3.11 billion to $5.76 billion and represents 18.7% to 34.6% of the benchmark annual funding level of $450 million (Table D-5).
- For the Early Start feed vector liquid converted to grout at a vendor facility and then transported to Clive and/or to WCS for disposal until 2040, the total cost ranges from $1.13 billion to $1.97 billion and represents 21.0% to 36.5% of the benchmark annual funding level of $450 million (Table D-6). The percent of total cost is similar, while the total cost is lower because this is a 12-year campaign compared to a 37-year campaign in Early Start with all waste disposed of offsite.

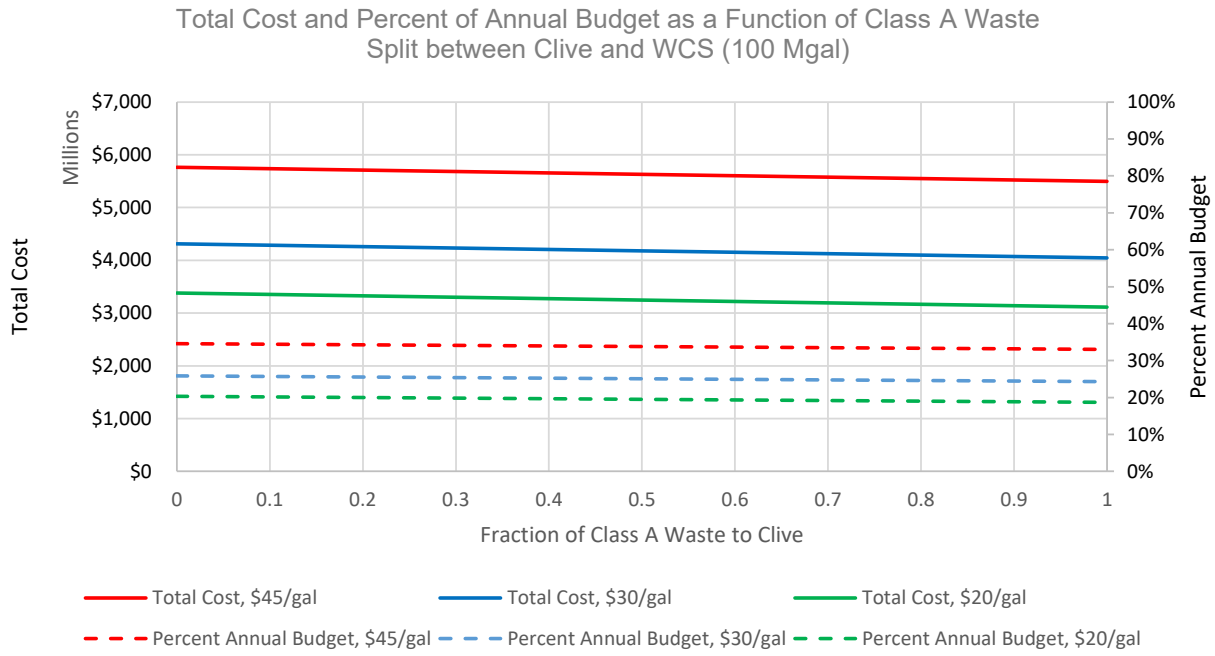
Table D-5. Off-Site Grout Disposal Costs, Early Start Feed Vector, Grouting by a Vendor

Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$5,760,813,526	34.6%	$4,310,836,837	25.9%	$3,379,881,053	20.30%
0.1	$5,734,306,379	34.4%	$4,284,329,689	25.7%	$3,353,373,906	20.14%
0.2	$5,707,768,231	34.3%	$4,257,791,542	25.6%	$3,326,835,758	19.98%
0.3	$5,681,261,083	34.1%	$4,231,284,394	25.4%	$3,300,328,611	19.82%
0.4	$5,654,722,936	34.0%	$4,204,746,247	25.3%	$3,273,790,463	19.66%
0.5	$5,628,203,788	33.8%	$4,178,227,099	25.1%	$3,247,271,316	19.50%
0.6	$5,601,696,641	33.6%	$4,151,719,952	24.9%	$3,220,764,168	19.34%
0.7	$5,575,158,493	33.5%	$4,125,181,804	24.8%	$3,194,226,020	19.18%
0.8	$5,548,639,346	33.3%	$4,098,662,656	24.6%	$3,167,706,873	19.03%
0.9	$5,522,132,198	33.2%	$4,072,155,509	24.5%	$3,141,199,725	18.87%
1	$5,495,594,050	33.0%	$4,045,617,361	24.3%	$3,114,661,578	18.71%
Max Increase	**4.60%**		**6.15%**		**7.85%**	

Table D-6. Off-Site Grout Disposal Costs, Early Start Feed Vector, Grouting by a Vendor, Off-Site Disposal until 2040

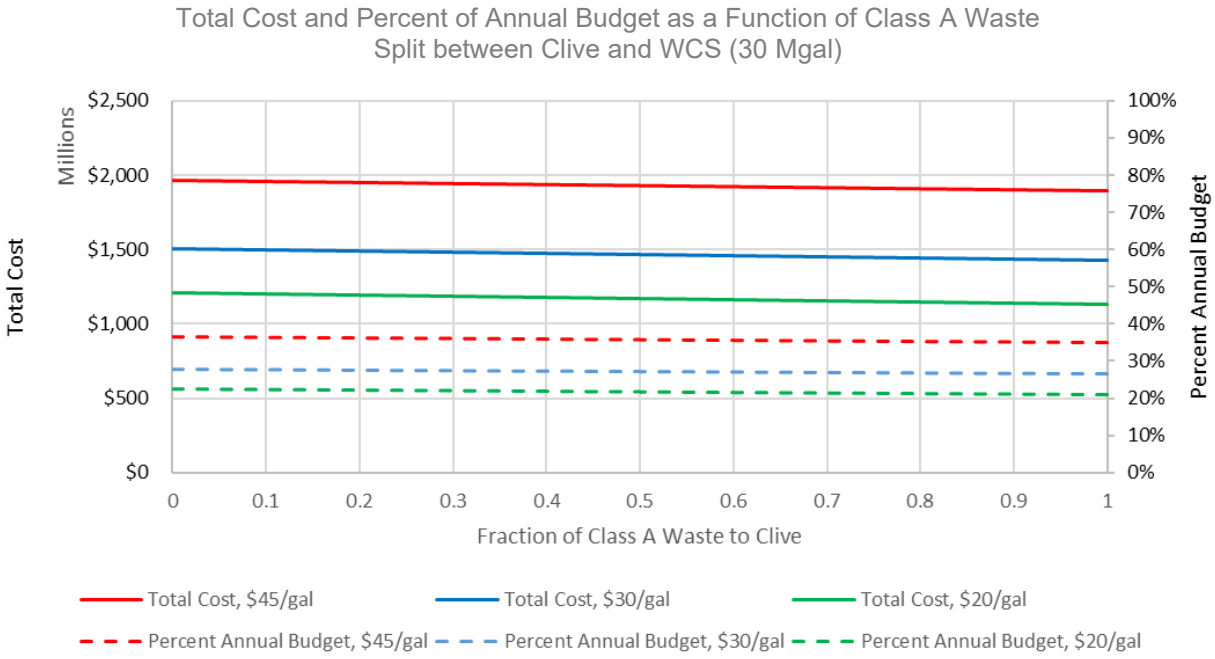
Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$1,968,654,218	36.5%	$1,506,303,160	27.9%	$1,209,451,221.71	22.40%
0.1	$1,961,119,385	36.3%	$1,498,768,328	27.8%	$1,201,916,388.96	22.26%
0.2	$1,953,553,553	36.2%	$1,491,202,495	27.6%	$1,194,350,556.21	22.12%
0.3	$1,946,018,720	36.0%	$1,483,667,662	27.5%	$1,186,815,723.46	21.98%
0.4	$1,938,452,887	35.9%	$1,476,101,829	27.3%	$1,179,249,890.71	21.84%
0.5	$1,930,918,054	35.8%	$1,468,566,997	27.2%	$1,171,715,057.96	21.70%
0.6	$1,923,371,222	35.6%	$1,461,020,164	27.1%	$1,164,168,225.21	21.56%
0.7	$1,915,805,389	35.5%	$1,453,454,331	26.9%	$1,156,602,392.46	21.42%
0.8	$1,908,270,556	35.3%	$1,445,919,498	26.8%	$1,149,067,559.71	21.28%
0.9	$1,900,704,723	35.2%	$1,438,353,666	26.6%	$1,141,501,726.96	21.14%
1	$1,893,169,891	35.1%	$1,430,818,833	26.5%	$1,133,966,894.20	21.00%
Max increase	**3.83%**		**5.01%**		**6.24%**	

Figure D-17 through Figure D-20 compare the transportation, disposal, and grout generation costs. The grout generation costs are the highest ones, reflecting the $20/gal to $45/gal treatment cost range, and the transportation costs are the lowest contributors to total cost. This explains why the total cost only slightly increases when all Class A grout is disposed of at WCS.



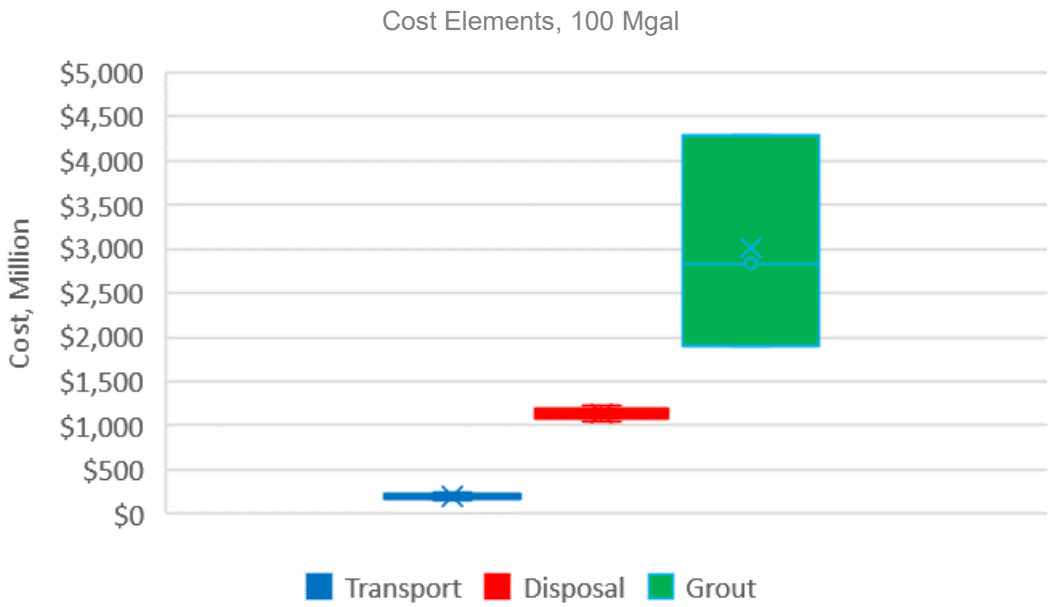
Note: 100 Mgal refers to the total volume of the liquid feed.

Figure D-17. Total Grout Disposal Cost and Percent Annual Budget, Early Start Feed Vector



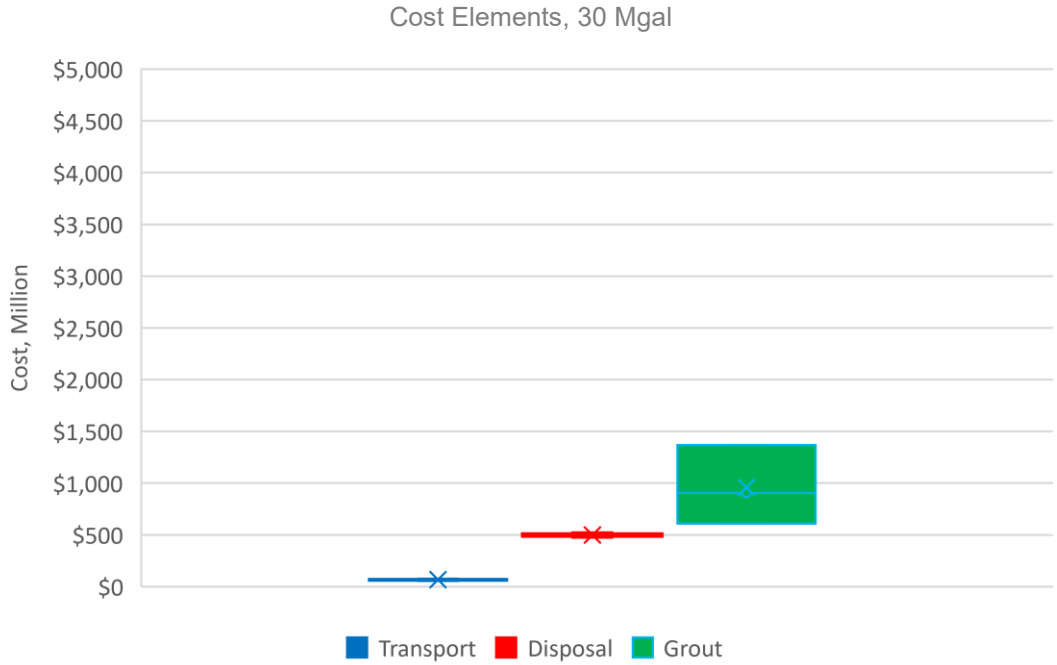
Note: 30 Mgal refers to the total volume of the liquid feed.

Figure D-18. Total Grout Disposal Cost and Percent Annual Budget, Early Start Feed Vector, Disposal until 2040



Note: 100 Mgal refers to the total volume of the liquid feed.

Figure D-19. Grout Disposal Cost Elements, Early Start Feed Vector



Note: 30 Mgal refers to the total volume of the liquid feed.

Figure D-20. Grout Disposal Cost Elements, Early Start Feed Vector, Off-Site Disposal until 2040

If the liquid supplemental LAW feeds are converted to grout at Clive or/and WCS, the transportation costs will be different while the grout generation and disposal costs will be the same as in Table D-5 and Table D-6. The transportation cost of liquids is higher in the Early Start feed vector than in the Early Start feed vector with off-site disposal until 2040. The difference in liquid transportation costs compared to grout will have small impact on the total cost because the transportation costs are small a fraction of the total costs.

D.3.7 Transportation Risks

The transport of goods by truck and railcar increases the amount of traffic, which increases the likelihood of traffic accidents and fatalities, in addition to increasing impacts to air quality, noise, and infrastructure. Statistically, these impacts are largely proportional to the number of miles traveled and independent of the cargo (i.e., transportation risks of transporting concrete blocks and transporting radioactive grout are the same). However, transporting radioactive materials does incur some additional risks, including potential doses to workers and the public from routine transport and from transportation accidents.

NEPA requires federal agencies to prepare an assessment of potential environmental impacts for major federal-sponsored actions that could impact the environment and other factors. Actual implementation of a shipping program, such as outlined here, would require the development of a NEPA assessment that would detail potential impacts to air quality, ecological resources, historic and cultural resources, noise, the public, and occupational health. Previous environmental impact statements (EIS) prepared for other DOE transportation programs provide analogs for risks for proposed shipping campaigns to WCS or Clive.

As an example, DOE/EIS-0337F, *West Valley Demonstration Project Waste Management Environmental Impact Statement, Final Summar*y (WVDP EIS), provides an example of an EIS for a major transportation program, including the shipping of LLW by rail to a disposal facility. The technical details of this EIS transportation analysis are presented in Appendix D of DOE/EIS-0337F.

Transportation Risks from Hanford to Waste Control Specialists

Many of the non-radiological transportation risks are proportional to the miles traveled, and some of the relative, non-radiological risks can be assessed by scaling the analysis from an analogous EIS of the safety of rail transport of other radioactive wastes. The WVDP EIS includes a non-radiological transportation risk assessment that can be scaled to provide a sense of the relative risks of this transportation program.

The closest analogy from the WVDP EIS to the proposed program to transport immobilized LAW from Hanford to the commercial WCS disposal facility is based on the following in the WVDP EIS: Alternative A, rail transport of all LLW and MLLW from WVDP to Hanford (Hanford was once considered a regional disposal facility for DOE-titled LLW). Specifically, under Alternative A, DOE would ship Class A, B, and C LLW (19,200 m^3) and MLLW (221 m^3) to the potential DOE disposal site in Washington State. Although not an exact match, the two transportation programs are very similar, with both programs assessing the impacts of rail transport of LLW and MLLW over ~2,400 mi.

Transportation impacts for rail transport from the WVDP EIS (DOE/EIS-0337F) for Alternative A for all LLW and MLLW for the 2,614-mi trip are presented in Appendix D, Table D-16 of the WVDP EIS and summarized in Column 3 of Table H-14 of Volume II, Appendix H of this report. The WVDP EIS transportation analysis is based on rail accident rates compiled in 1999 (DOE/EIS-0337F, page D 11). These rates were adjusted for freight train accidents for the periods from 2013 to 2022.

Programmatic Risks

This Fiscal Year 2021 National Defense Authorization Act, Section 3125 (NDAA21-3125) study completed a semi-quantitative assessment of risks, based on an elicitation of subject matter experts. This elicitation of risks identified:

- Initiating scenarios that could result in deviations from the design/operational intent
- The probability of the initiating scenario
- The unmitigated consequences
- The means of mitigating such events
- A probability of a successful mitigation
- The cost and schedule consequences of the mitigation.

This semi-quantitative assessment of risks identified and analyzed one programmatic risk for the off-site transportation program: political opposition in a major city on the rail route following a rail accident causes DOE to temporarily stop the shipping program. Based on experience, the probability of this occurring is low; however, the unmitigated consequences were judged to be very high costs and very high schedule impacts.

The mitigation strategy is to change the rail route or shift to shipping by truck. The probability of mitigation success is very high, and the mitigation consequences were assessed to be low cost and low schedule. To avoid the risk of site-specific interruptions of such shipments, agreements with multiple immobilization and disposal sites are important and should be in effect for any such multi-year or multi-decade campaign.

Another strategy is to ensure that both off-site permits/permit modifications (if any are needed), and agreements with off-site facilities, are in place prior to initiation of any on-site grouting or any shipment of liquid supplemental LAW for off-site treatment/disposal. Such agreements could ideally provide for alternative off-site contingency disposition arrangements in the event that the contracted receiving facility cannot disposition the waste as expected. Currently, Energy*Solutions* and WCS dispose of wastes received from the government, medical facilities, industry, and utilities. Liquid waste that is received is converted to solid waste before disposal. There has not been substantive stakeholder or political resistance to specific waste streams being disposed of at these sites, except for depleted uranium, which DOE proposed to dispose of at the Energy*Solutions* Clive site. Neither of the facilities has ever declined a waste receipt, because both facilities have an ability to treat the waste in case if it does not meet the acceptance criteria. In one case, DOE decided to recall the waste shipment sent for an off-site disposal.

Another programmatic risk considered in the analysis is the potential unavailability of the two off-site disposal facilities for either untreated liquids or solidified LAW. Energy*Solutions* (Clive) typically receives over 28,317 m^3 (1 million ft^3) of LLW for disposal on an annual basis, with some years exceeding 141,584 m^3 (5 million ft^3).

Analysis of the feed vectors for supplemental LAW indicates that approximately 15% of any grouted supplemental LAW generated will be greater than Class A waste, indicating, as analyzed in Section D.3.3, that there is significant flexibility between sending the bulk of either treated or untreated supplemental LAW to either Energy*Solutions* Clive or WCS, Additionally, as noted in Section D.2, the expected volume of waste is not expected to oversubscribe available disposal volume at either site.

DOE's commitment to safety is integrated into all its activities and requirements, including the transportation of hazardous materials. Annually, about three million radioactive materials packages are shipped in the United States by highway, rail, air, and water. In 2020, DOE made over 3,200 hazardous material shipments, covering a combined distance of over 6 million miles. Since fiscal year 2004, the DOE Office of Environmental Management has completed over 184,000 shipments of radioactive material and waste, including liquid LLW shipments to commercial treatment facilities.

Examples of liquid radioactive waste shipments include:

- The successful closure of the DOE Rocky Flats site in Colorado in 2005 was facilitated by more than 1.5 million gallons of liquid radioactive waste shipments to a permitted/licensed commercial treatment and disposal facility in Clive, Utah.
- In 2017, DOE's West Valley Demonstration Project in New York shipped approximately 1,000 gallons of liquid LLW by truck to a permitted/licensed commercial facility in Andrews County, Texas, for treatment and disposal.
- In 2012, DOE's Portsmouth Gaseous Diffusion Plant in Ohio shipped approximately 4,700 gallons of radiologically contaminated aqueous hydrogen fluoride by truck to a permitted/licensed commercial facility in Andrews County, Texas, for treatment and disposal as LLW.
- During the past decade, the Separations Process Research Unit in New York shipped approximately 150,000 gallons of liquid LLW by truck to a permitted/licensed commercial treatment facility in Richland, Washington, for treatment.

In addition, DOE works closely with state, tribal and local jurisdictions on transportation-related topics. Specifically, DOE has established a National Transportation Stakeholder Forum to engage at a national level with these stakeholders regarding DOE's shipments of radioactive materials and waste. The DOE Transportation and Emergency Preparedness Program conducts courses in emergency preparedness with state, tribal and local emergency responders to ensure that they have the necessary training and tools to respond to any transportation accidents involving DOE radioactive material shipments.

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Appendix E. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

E.1 INTRODUCTION

The Federally Funded Research and Development Center (FFRDC) team developed the crosswalk in Table E-1 to confirm that all criteria from Section 3125 of the *National Defense Authorization Act for Fiscal Year 2021* (NDAA21) were addressed in the FFRDC analysis and to indicate where in the taxonomy of decision-informing criteria each NDAA21 element was evaluated.

E.2 CROSSWALK

Table E-1. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

H.R. 6395[a] – 995 element	FFRDC Report Taxonomy Criteria[b]
3125(c)(1)(A): The maturity and complexity of the technology	Criterion 3.1.1.2: Process complexity Criterion 3.1.1.5: Technology maturity
3125(c)(1)(B): The extent of previous use of the technology	Criterion 3.1.1.5: Technology maturity
3125(c)(1)(C): The lifecycle costs and duration of use of the technology	Criterion 2.1: Specific risks or benefits related to ongoing tank degradation Criterion 2.4: Duration Criterion 3.2: Likelihood and consequences of failing to complete due to resource constraints Criterion 4: Lifecycle costs (discounted present value)
3125(c)(1)(D): The effectiveness of the technology with respect to immobilization	Criterion 1.1.2: Mobility of primary and secondary wastes to a groundwater source Criterion 1.2.2: Confidence in immobilization with regard to groundwater
3125(c)(1)(E): The performance of the technology expected under permanent disposal	Criterion 1.1: Residual threat to health and environment upon successful completion Criterion 1.2: Long-term risks upon successful completion
3125(c)(1)(F): The topical areas of additional study required for the grout option identified in [the prior report]	Volume II, Appendix A provides details of additional studies considered and incorporated into the scoring against the taxonomy criteria.
3125(c)(2): The differences among approaches	Comparison of top-level assessed criteria scores, as presented in Section 5.0 of the report.
3125(c)(3): The compliance of such approaches with the technical standards described in 3134(b)(2)(D) of the FY 2017 NDAA[c] (i.e., CERCLA, RCRA, Clean Air and Clean Water Acts)	Criterion 1.1: Residual threat to health and environment upon successful completion Criterion 1.2.2: Confidence in immobilization with regard to groundwater Criterion 2.2: Risks to humans (during construction and operations) Criterion 2.3: Risks to the environment (during construction and operations) Criterion 5: Securing and maintaining necessary permits/authorities (regulatory approval)

Table E-1. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

H.R. 6395[a] – 995 element	FFRDC Report Taxonomy Criteria[b]
3125(c)(4): The differences among potential disposal sites for the waste form produced through such treatment	Assessed throughout the taxonomy on an alternative-by-alternative basis for effectiveness, risk, and regulatory impacts. Geological differences were primarily assessed under 1.1 and 1.2; transportation and handling risks were assessed under 2.2 and 2.3.
3125(c)(5)(A): Regulatory compliance	Criterion 1: Long-term effectiveness (environmental and safety risk after disposal) Criterion 5: Securing and maintaining necessary permits/authorities (regulatory approval)
3125(c)(5)(B): Public acceptance	Criterion 6: Community/public acceptance (state/local)
3125(c)(5)(C): Cost	Criterion 3.2: Likelihood and consequences of failing to complete due to resource constraints Criterion 4: Lifecycle cost (discounted present value)
3125(c)(5)(D): Safety	Criterion 2.2: Risks to humans (other than tank degradation)
3125(c)(5)(E): The expected radiation dose to maximally exposed individuals over time	Criterion 1.2.2: Confidence in immobilization with regard to groundwater Criterion 2.2.1.1: Radiation
3125(c)(5)(F): Differences among disposal environments	Assessed throughout the taxonomy on an alternative-by-alternative basis for effectiveness, risk, and regulatory impacts. Geological differences were primarily assessed under 1.1 and 1.2; transportation and handling risks were assessed under 2.2 and 2.3.
3125(c)(6): How much and what type of pretreatment is needed to meet regulatory requirements regarding long-lived radionuclides and hazardous chemicals	No alternatives were scored that were not assessed as highly likely to meet community standards for the relevant contaminants in the planned disposal site. For some alternatives, this meant that specified pretreatment processes (e.g., technetium and/or iodine removal) were included in the definition of the alternative and in associated cost, schedule, and risk assessments.
3125(c)(7): Whether the radionuclides can be left in the waste form or economically removed and bounded at a system level […] and how to account for the secondary waste stream.	Primary and secondary waste streams were considered in assessment of all criteria. Whether to remove radionuclides through pretreatment was specified as part of the definition of the alternative being assessed.
3125(c)(8)(A): The costs and risks in delays with respect to tank performance over time	Criterion 2.1: Specific risks or benefits related to ongoing tank degradation
3125(c)(8)(B): Consideration of experience with treatment methods at other sites and commercial facilities	Criterion 3.1.1.5: Technology maturity, MOE #2: Demonstrated effectiveness elsewhere (including Test Bed Initiative) and MOE #3: Analogous DOE experience

Table E-1. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

H.R. 6395[a] – 995 element	FFRDC Report Taxonomy Criteria[b]
3125(c)(8)(C): Outcomes of the Test Bed Initiative of the Hanford Office of Environmental Management	Criterion 3.1.1.5: Technology maturity, MOE #2: Demonstrated effectiveness elsewhere (including Test Bed Initiative) and MOE #3: Analogous DOE experience

[a] *National Defense Authorization Act for Fiscal Year 2021*, Public Law 116–283, January 1, 2021 (also known as the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021).

[b] The full taxonomy of assessment criteria used in this report is provided in Volume I, Appendix A.

[c] *National Defense Authorization Act for Fiscal Year 2017*, Public Law 114–328, December 23, 2016.

CERCLA = Comprehensive Environmental Response, Compensation, and Liability Act.
DOE = U.S. Department of Energy.
FFRDC = Federally Funded Research and Development Center.
MOE = measure of effectiveness.
NDAA = National Defense Authorization Act.
RCRA = Resource Conservation and Recovery Act.

E.3 REFERENCES

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Follow-on Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation: Supporting Information

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LIST OF ABBREVIATIONS

^{3}H	hydrogen-3
^{14}C	carbon-14
^{79}Se	selenium-79
^{85}Kr	krypton-85
^{90}Sr	strontium-90
^{99}Tc	technetium-99
^{127}I	iodine-127
^{129}I	iodine-129
AAR	Association of American Railroads
ACI	American Concrete Institute
AEA	Atomic Energy Act
ALARA	as low as reasonably achievable
AoA	analysis of alternatives
ARP	actinide removal process
ASTM	ASTM International
BBI	Best Basis Inventory
BDAT	Best Demonstrated Available Technology
BFS	blast furnace slag
BSR	bench-scale reformer
BWF	Bulk Waste Disposal and Treatment Facilities
CAA	Clean Air Act
CAPEX	capital expenditure
CAW	Class A West
CBO	Congressional Budget Office
CD	Critical Decision
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CETL	Clemson Engineering Technologies Laboratory
CFR	Code of Federal Regulations
CIF	Consolidated Incineration Facility
CLSM	controlled low-strength material
CNWRA	Center for Nuclear Waste Regulatory Analysis
CO	carbon monoxide
CO	Colorado
CoC	contaminant of concern
CoPC	constituent of potential concern
Cr	chromium
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
CRR	carbon reduction reformer
Cs	cesium
CSSX	caustic-side solvent extraction

CST	crystalline silicotitanate
CSTR	continuous stirred tank reactor
CWA	Clean Water Act
D&D	decontamination and decommissioning
DBVS	Demonstration Bulk Vitrification System
DF	decontamination factor
DFHLW	direct-feed high-level waste
DFLAW	direct-feed low-activity waste
DMR	denitration and mineralizing reformer
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-EM	U.S. Department of Energy, Office of Environmental Management
DOE-OPT	U.S. Department of Energy, Office of Packaging and Transportation
DOT	U.S. Department of Transportation
DRC	Division of Radiation Control
DRF	dry reagent formulation
DSS	double-shell slurry
DSSF	double-shell slurry feed
DST	double-shell tank
DU	depleted uranium
DWPF	Defense Waste Processing Facility
DWS	Drinking Water Standards
DWTS	dry waste transfer system
Ecology	Washington State Department of Ecology
EDTA	ethylenediamine-tetraacetic acid
EIS	environmental impact statement
EM	U.S. Department of Energy, Office of Environmental Management
EMCBC	U.S. Department of Energy, Environmental Management Consolidated Business Center
EMF	Effluent Management Facility
EPA	U.S. Environmental Protection Agency
ERDF	Environmental Restoration Disposal Facility
ETF	Effluent Treatment Facility
EWIS	Electronic Waste Information System
FA	fly ash
FBSR	fluidized bed steam reforming
FFRDC	Federally Funded Research and Development Center
FMF	Fuel Manufacturing Facility
FWF	Federal Waste Disposal Facility
FY	fiscal year
GAAT	Gunite and Associated Tanks
GAC	granular activated carbon
GAO	U.S. Government Accountability Office

GCL	geosynthetic clay liner
GDU	grout disposal unit
GFC	glass-forming chemical
GTCC	Greater-than-Class C
GWPL	groundwater protection level
GWQS	Ground Water Quality Standard
HEDTA	hydroxyethylethylenediaminetriacetic acid
HELP	Hydrologic Evaluation of Landfill Performance
HEPA	high-efficiency particulate air
HFPEM	High-Level Waste Feed Preparation and Effluent Management
HIC	high integrity container
HLVIT	high-level [mixed radioactive waste] vitrification
HLW	high-level waste
HRWR	high-range water reducer
HVAC	heating, ventilation, and air conditioning
HWMA	Hazardous Waste Management Act
I	iodine
IAEA	International Atomic Energy Agency
IC	institutional control
ICV	In-Container Vitrification[1]
IDF	Integrated Disposal Facility
ILAW	immobilized low-activity waste
ILW	intermediate level waste
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
IOC	iron oxide catalyst
IP	industrial package
IQRPE	Independent Qualified Registered Professional Engineer
ISO	International Organization for Standardization
IWTU	Integrated Waste Treatment Unit
IX	ion exchange
K_d	dissociation constant
K_{sp}	solubility product constant
LANL	Los Alamos National Laboratory
LARW	low-activity radioactive waste
LAW	low-activity waste
LAWPS	Low-Activity Waste Pretreatment System
LAWST	low-activity waste supplemental treatment
LCC	lightweight cellular concrete
LCRS	leachate collection and removal system
LDR	Land Disposal Restrictions

[1] In-Container Vitrification (ICV) is a trademark of Veolia, Boston, Massachusetts.

LDS	leak detection system
LERF	Liquid Effluent Retention Facility
LFE	low-activity waste feed evaporator
LLHH	long, large, and/or heavy hazardous
LLRW	low-level radioactive waste
LLW	low-level waste
LSA	low specific activity
LSW	liquid secondary waste
MCC	modular concrete canister
MCL	maximum contaminant level
MCU	modular caustic-side solvent extraction unit
MDL	method detection limit
MF	MasterFlow®
MIMS	Manifest Information Management System
MLLW	mixed low-level waste
MOE	measure of effectiveness
MST	monosodium titanate
MT	metric ton
NaOH	sodium hydroxide
NARM	naturally occurring and accelerator-produced radioactive material
NAS	National Academy of Sciences
NASEM	National Academy of Sciences, Engineering, and Medicine
NCP	National Contingency Plan
NDA	Nuclear Decommissioning Authority
NDAA	National Defense Authorization Act
NDAA17	Fiscal Year 2017 National Defense Authorization Act
NDAA21	Fiscal Year 2021 National Defense Authorization Act
NEPA	National Environmental Policy Act
NNSS	Nevada National Security Site
NORM	naturally occurring radioactive material
NO_x	nitrogen oxides
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NRSB	Nuclear and Radiation Studies Board
NSDWR	National Secondary Drinking Water Regulations
NY	New York
O	Order
OAG	Ogallala, Antlers, and Gatuna
OH	Ohio
OMB	U.S. Office of Management and Budget
OPC	ordinary portland cement
OPEX	operations expenditure

ORNL	Oak Ridge National Laboratory
ORP	U.S. Department of Energy, Office of River Protection
OU	Operable Unit
PA	performance assessment
PCB	polychlorinated biphenyl
PCT	product consistency test
PE	performance evaluation
Perma-Fix Northwest	Perma-Fix Northwest, Inc.
PGF	process gas filter
PNNL	Pacific Northwest National Laboratory
PT	Pretreatment Facility
PUF	pressurized unsaturated flow
PUREX	plutonium-uranium extraction
PV	present value
R&D	research and development
RADTRAN	Radioactive Material Transport
RCRA	Resource Conservation and Recovery Act
RCW	Revised Code of Washington
RD&D	research, development, and demonstration
REDOX	reduction-oxidation
RLWTF	Radioactive Liquid Waste Treatment Facility
RML	radioactive material license
ROD	record of decision
RPP	River Protection Project
SALDS	state-approved land disposal site
SAS	steam atomized scrubber
SBS	submerged bed scrubber
SBWW	sodium-bearing wastewater
SCDHEC	South Carolina Department of Health and Environmental Control
SCR	selective catalytic reduction
SDU	Saltstone Disposal Unit
SDWA	Safe Drinking Water Act
Se	selenium
SER	Safety Evaluation Report
SLAW	supplemental low-activity waste
SLDS	secondary leak detection system
SMCL	secondary maximum contaminant level
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SPF	Saltstone Production Facility
SPFT	single-pass flow-through

SPRU	Separations Process Research Unit
sRF	spherical resorcinol-formaldehyde
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SSR	Specific Safety Requirements
SST	single-shell tank
SSW	solid secondary waste
START	Stakeholder Tool for Assessing Radioactive Transportation
SVOA	semivolatile organic analyte
SVOC	semivolatile organic compound
SWPF	Salt Waste Processing Facility
TAC	Texas Administrative Code
TBI	Test Bed Initiative
Tc	technetium
TC&WM	Tank Closure and Waste Management
TCAS	Texas Constitution and Statutes
TCEQ	Texas Commission on Environmental Quality
TCLP	Toxicity Characteristic Leaching Procedure
TCO	thermal catalytic oxidizer
TDS	total dissolved solids
TEDF	Treated Effluent Disposal Facility
TFF	Tank Farm Facility
TFPT	Tank Farms Pretreatment
THOREX	thorium extraction
TI	transportation index
TO	thermal oxidizer
TOC	total organic carbon
TOE	total operating efficiency
TPA	Tri-Party Agreement
TRAGIS	Transportation Routing Analysis Geographic Information System
TRL	technology readiness level
TRU	transuranic
TSCR	tank-side cesium removal
TSD	treatment, storage, and disposal
TSDF	Texas Storage and Processing Facility
TVS	Transportable Vitrification System
TWINS	Tank Waste Information Network System
TX	Texas
U.K.	United Kingdom
U.S.	United States
UAC	Utah Administrative Code
UDEQ	Utah Department of Environmental Quality

UMTRA	Uranium Mill Tailings Remediation Action
UT	Utah
UTS	Universal Treatment Standards
UV/OX	ultraviolet/oxidation
UWQB	Utah Water Quality Board
VHT	vapor hydration test
VLAW	vitrified low-activity waste
VOA	volatile organic analyte
VOC	volatile organic compound
VSL	Vitreous State Laboratory of The Catholic University of America
VTD	vacuum thermal desorption
WA	Washington
WAC	Washington Administrative Code
WCS	Waste Control Specialists, LLC
WDOH	Washington Department of Health
WebTRAGIS	Web-Based Transportation Routing Analysis Geographic Information System
WESP	wet electrostatic precipitator
WIPP	Waste Isolation Pilot Plant
WIR	Waste Incidental to Reprocessing
WRF	waste receiving facility
WRPS	Washington River Protection Solutions, LLC
WTP	Waste Treatment and Immobilization Plant
WVDP	West Valley Demonstration Project
XAS	X-ray absorption spectroscopy

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Appendix A. Recent Grout Advances

A.1 INTRODUCTION

The term "grout" can have various interpretations ranging from an engineered material to produce specific properties for a solid waste form to a simple at-home use material that would likely not be suitable for radioactive waste immobilization. Within the U.S. Department of Energy (DOE) complex, the term "grouting" is used to describe low or ambient temperature processes through which water or liquid waste is mixed with inorganic dry materials (pozzolanic, polymeric or supplementary) and cured to produce a solid waste form (grout). The terms stabilization, solidification, and encapsulation have specific technical definitions and are sometimes used to describe similar ambient temperature waste treatment processes that produce waste forms designed to meet certain performance criteria (e.g., strength, contaminant retentions). The term "grout" was first applied in the early 1960s to a mixture of aqueous radioactive waste-cement-clay-pozzolan for deep well hydrofracture injection and geologic isolation in the Conasauga Shale formation at the Oak Ridge Reservation (ORNL-4259, *Engineering Development of Hydraulic Fracturing as a Method for Permanent Disposal of Radioactive Wastes*, and Tamura 1967). For consistency, the term "grout" will be used to describe the ambient and low temperature processes within this report. In all cases, the final product is assumed to have properties designed to meet performance requirements for disposal.

The primary components of grouts typically include cement, ground granulated blast furnace slag (BFS), coal combustion fly ash (FA), silica fume, metakaolin, natural volcanic ash or glass, barite, iron oxides, or other materials for shielding. Additives (e.g., clays or other components such as getters) may be used for targeted retention of specific waste constituents. Numerous types of cement are used for waste treatment depending on the stabilization and processing needs (e.g., portland cement [calcium silicate], slag cement, calcium aluminate cement, calcium sulfoaluminate cement, and various phosphate cements). These cements react with water to form low solubility hydrated phases within the waste form matrix. Other material types used to produce low temperature waste forms include calcium sulfate cement, geopolymers (aluminosilicate precursor that hardens/crosslinked by condensation reactions with alkalis, and water to form a solid), zeolites, clays, and organic polymer waste forms.

Cementation (grouting) is the treatment of choice in the international community for low-level waste (LLW) treatment for final near-surface disposal; and as such, the processes have gained consideration as a supplemental low-activity waste (LAW) treatment and immobilization technology. Grout waste forms have several advantageous properties that are covered in more detail in this appendix and the entirety of the report, including:

- Lower capital and operating costs compared to high temperature processes due to greater process simplicity, limited amount of secondary waste, much smaller facility footprint, and reduced need for engineered safety systems
- A significant history of managing Resource Conservation and Recovery Act (RCRA) and mixed waste streams with disposal at a variety of sites and under RCRA grouting (solidification or stabilization) is the Best Demonstrated Available Technology (BDAT) for inorganic wastes that require treatment prior to land disposal
- Wide availability and low cost of mostly dry ingredients with the potential for sustainable reuse of industrial process by-products otherwise stockpiled and directly disposed of
- The capability of a chosen matrix to be effective over a variety of waste feed chemistries or the capability to tailor formulations to specific feed compositions
- Minimal power requirements
- Possibility for modular local deployment.

Drawing on these advantages, grouts have been used throughout the DOE complex at the Hanford Site, Savannah River Site (SRS), West Valley Demonstration Project (WVDP), Oak Ridge Reservation, and Idaho National Laboratory (INL), along with extensive use in the commercial nuclear industry. Specifics on these efforts are provided in Section A.3.

This appendix reviews information on grout relevant to the alternatives discussed in Section 3.3. Each subsection opens with a high-level summary of the detailed information provided. An overview of the basis for grout waste forms is provided in Section A.2. A review of research and development (R&D) efforts relevant to Hanford LAW since the analysis required by Section 3134 of the National Defense Authorization Act for FY 2017 (NDAA17), documented in SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*, and that address the "next steps" in that report, is provided in Section A.3. A technology overview and relevant considerations are included in Section A.4.

A.2 GROUT BACKGROUND

A.2.1 Grout Formation

This subsection provides an overview of how grout waste forms are made, their resulting composition, and how key waste compounds behave within the resulting material. This information provides a technical basis for the assessments of grout durability and waste form performance that are addressed throughout this document. In summary, grout waste forms are made up of a range of different mineral phases (depending on the ingredients and waste feed) that control the properties of the waste form and how waste compounds are retained within the waste form (i.e., some contaminants will be found in the pore space of the waste form while others can be bound to or incorporated into the matrix).

Grout waste forms are produced by ambient temperature processes that involve the hydration or polymerization of dry reagents to generate a network of matrix phases producing a solid mass. For example, Saltstone and Cast Stone are two formulations made by mixing liquid waste with BFS, FA, and a smaller fraction of portland cement. The Cast Stone formulation being 47 wt% BFS, 45 wt% FA, and 8 wt% OPC while Saltstone was nominally 45 wt% BFS, 45 wt% FA, and 10 wt% OCP. However, Saltstone has an operational range of 20 wt% - 60 wt% BFS (now slag cement), 20 wt% - 60 wt% FA (now thermally beneficiated Class F FA), and 0 wt% - 10 wt% OPC. The resulting matrix phases in grout waste forms comprising portland cement, slag cement (ground granulated blast furnace slag), and supplemental cementitious materials include poorly crystalline low solubility hydrate phases (gels) and crystalline hydrated solids. Portlandite ($Ca(OH)_2$) and gypsum ($CaSO_4$) are the most soluble phases generated in cement-only grout and would be more likely to dissolve and form new minerals over time. Whereas calcium-silicate-hydrates, like 11 Å tobermorite ($Ca_5Si_6O_{16}(OH)_2 \bullet 4H_2O$), are generally the least soluble and likely to remain unaltered over time. Of course, the evolution of these heterogenous grout structure will depend on the morphology and particle size of these phases as much as their composition. Formation of calcium-silicate-hydrates is promoted in grouts with the addition of BFS, FA, or silica fume to portland cement or when grouts are based primarily on BFS that are activated with caustic solutions (e.g., the Cast Stone dry blend made with alkaline LAW). These matrix phases have a range of morphologies and particles sizes from submicrons to microns, producing a heterogeneous microstructure. The phase assemblages depend on the bulk oxide composition of the reactive cement compounds and waste feed (SRNL-STI-2014-00397, *X-Ray Diffraction of Slag-Based Sodium Salt Waste Forms*).

The waste loading that can be achieved for grout waste forms includes the water in the liquid waste that becomes stabilized within the network of matrix phases. By contrast, high temperature thermal processes (i.e., vitrification, steam reforming) drive off the water that must be treated as an airborne emission or a secondary liquid waste stream.

The primary mechanisms for contaminant stabilization in grout waste forms are that contaminants can: (1) occupy lattice positions in matrix phases (e.g., selenium substitution for sulphate in ettringite [Zhang and Reardon 2003]), (2) be physically sorbed or chemically bound on the surfaces of the matrix particles (e.g., arsenic sorption onto iron-oxide cement [Kundu and Gupta 2006]), and (3) precipitated as low solubility species (e.g., Cr(III) and Tc(IV) in reducing grout). Many anions will remain in the pore solution in the waste form, and the release would be controlled by the physical transport pathways in the waste form (e.g., NO_3^-, NO_2^-, I^-, $Tc(VII)O_4^-$). However, recent works have shown that some of these contaminants (Tc and I) can incorporate into the matrix phases, providing improved retention (Bourchy et al., 2022; Gillispie et al., 2020; Guo et al., 2020; Saslow et al., 2020; VSL-21R5000-1, *Development of Improved Grout Waste Forms for Supplemental Low Activity Waste Immobilization*). Other anions such as Cl^-, have binding capacity in the matrix and while some oxyanions (SO_4^{2-} and CO_3^{2-}) are involved in generating hydrated phases combining with cations. This is contrary to a glass waste form where contaminants either become part of, or are, encapsulated in the glass lattice structure.

While many of the matrix phases in grout have low solubilities in water, the phases can evolve with time due to environmental interactions. These environmental interactions occur due to the porous nature of the matrix structure. With the heterogeneous morphology and micron to submicron particle size of the binding matrix phases, a relatively large network of reactive surface area is created and available for reaction with infiltrating environmental water, gas, dissolved ions, or species released from the waste form itself. For example, SRS Saltstone has a transmissive porosity of between 40 and 60% (WSRC-STI-2007-00352, *Saltstone Variability Study – Measurement of Porosity*) but other formulations can be designed to have far lower porosity. It should be noted that a glass waste form would also have a degree of open space as it will be cracked in the canister, giving a ~ 10× increase in surface area (PNL-5947, *A Method for Predicting Cracking in Waste Glass Canisters*). As the matrix phases interact with the environment (and species released from the waste form itself) through the pore space, some conversions to silica- or alumina-gels occur. The timeframe over which this occurs depends on several factors such as the amount of water that contacts the waste form, exposure to open air, exposed surface area, advection, carbonation, and others.

These interactions with the environment and matrix phase evolution can induce various processes that drive mechanisms (e.g., cracking), which can alter the waste forms. As the waste forms alter, transport pathways for contaminants can be introduced leading to increased release, or processes can occur that slow the release of contaminants (e.g., pore clogging). Summaries of these mechanisms and processes are provided in PNNL-32458, *Evaluation of Degradation Mechanisms for Solid Secondary Waste Grout Waste Forms*, which is specific to Hanford, and CNWRA-2009-001, *Review of Literature and Assessment of Factors Relevant to Performance of Grouted Systems for Radioactive Waste Disposal*, which is specific to large closure grout. For near-surface disposal in an arid environment such as Hanford these processes occur over long timeframes from hundreds to tens of thousands of years.

A.2.2 Common Candidate Dry Reagents

Questions have been raised regarding what materials would be needed to support a grouting operation, their availability, how they would be managed, and how formulations can be tailored based on waste feed composition to ensure that waste acceptance criteria are met. Since a baseline formulation is not defined for the supplemental LAW treatment grout alternatives (only waste form properties and performance criteria have been assumed), many theoretical formulations could be used. Therefore, this subsection provides an overview of the most likely reagents and sources that can be used to produce grout waste forms. In summary, this subsection provides brief technical background on how the different reagents can contribute to making grout waste forms and shows many options would be available.

Several dry reagents could be used in a grout waste form depending on the waste to be immobilized and the required processing characteristics. The work to date using these reagents for Hanford LAW is summarized in Section A.3.3. Ensuring the quality of the reagents cannot be a forgotten requirement; for example, field spoil piles of fly ash at Hanford do not have the traceability nor purity required for waste immobilization. Brief descriptions of the most general cement reagents for immobilizing liquid waste are as follows.

Portland cement: Hydraulic cements are generally used for radioactive waste immobilization (Atkins and Glasser 1992). The composition of the most common hydraulic cements used for radioactive waste immobilization are based on calcium silicate compounds, such as the portland cements and blended portland cements (mixtures of pozzolans, slags, and other reactive and inert ingredients), calcium aluminate cements, calcium sulfoaluminate cements, lime-pozzolan cements, and slag cements.

Ordinary portland cement (OPC) is the most commonly used cement type for immobilizing liquid and wet solid radionuclide containing waste streams worldwide. The five classes of portland cements (ASTM C150/C150M-21, *Standard Specification for Portland Cement*) are based on mineral composition:

- Type I – General purpose cement
- Type II – Provides moderate resistance to sulphate attack
- Type III – Used when early high-strength is required
- Type IV – Used when low heat of hydration needed (e.g., large structures)
- Type V – Used when high sulphate resistance is needed.

Portland cements (and slag cements) are typically blended with mineral additives such as pozzolans or inert fillers (1) to control heat release by exothermic hydration reactions, (2) to reduce porosity and hydraulic conductivity, and (3) to enhance the phase assemblage to chemically stabilize selected radionuclides and hazardous contaminants (Paris et al., 2016). These blended formulations provide a wide range of properties and flexibility in designing waste forms. In most formulations, cement-based waste forms have an initial porewater pH of ≥12.

Calcium aluminate cements: Calcium aluminate cements and cement blends have been used in France for waste streams containing chemical species (e.g., boric acid) that retard the hardening process of portland cement. Calcium aluminate matrices are less alkaline (pH 10.5 to 11) than portland cement matrices (pH >12) and are, therefore, used for encapsulating reactive metal wastes that corrode in alkaline environments and could lead to hydrogen generation (Chavda et al., 2014). These cements are commonly fast setting with higher heat generation.

Calcium sulfoaluminate cements: Hydrated **c**alcium sulfoaluminate matrices, with ettringite and calcium mono-sulfoaluminate hydrate as main hydration products, are prepared from calcium sulfoaluminate clinker containing 15 to 25 wt% calcium sulfates (Péra and Ambroise, 2004). Both ettringite and monosulfoaluminate hydrate have crystalline structures that can incorporate or sequester a wide range of waste anions, such as chromate, sulfate, chloride, and carbonate and multivalent metal cations. Potential radioactive waste treatment applications include conditioning of borate waste streams, quenched incinerator off-gas waste containing chlorides, and sulfate waste streams. The pH of these systems is lower than that of hydrated portland cement and therefore is less corrosive to contaminated reactive metals such as aluminum.

Alkali-activated cements (slag cements): A variety of non-crystalline natural, manufactured, and industrial by-product materials rich in SiO_2 and Al_2O_3 can be activated with alkalis to produce cementitious type matrices (Shi and Fernández-Jiménez, 2006). Examples of by-products include ground granulated BFS and other slags, and coal FA. Alkaline activators include sodium or potassium hydroxides, silicates or carbonates.

Slag cement requires activation by NaOH, Na_2SO_4, Na_2CO_3, or Na silicate/other chemicals and is used as a partial replacement for portland cement in numerous construction applications (Wang et al., 1995). The slag cement is a byproduct in an iron-making blast furnace and is made by water quenching from a molten state (~1,550 °C). The resulting slag is then size reduced to a powder to increase the reactive surface area. Slag cement is 95 to 100% silicate glass, with minor components consisting of Al, Ca, Mg, Fe.

- **Slag cement and blends**: Slag cements are the commonly used reagents used for immobilizing alkaline (Na) salt liquid waste streams, because slag hydration is activated by the waste liquid and the resulting phase assemblage typically results in a lower hydraulic conductivity (permeability) than that of portland cement. Slag cement also results in a chemically-reducing environment, which is advantageous for chemically immobilizing selected radionuclides and hazardous constituents in alkaline media.
- **Super sulfated slag cements**: These blended cements consist of mixtures of BFS and calcium sulfate with a small quantity of portland cement used as the "activator" (Gruskovniak et al., 2008). This class of materials is also gaining interest for waste immobilization.

Acid-base cements (phosphate cements): Acid-base cements are formed by reacting an acid and a base, the resulting product is a salt (or hydrogel) that acts as the matrix (Prosser and Wilson, 1986). Non-hydraulic, acid-base cements can also be used for immobilization. The most common acid-base cements used for radioactive waste conditioning are phosphate-based. Ceramicrete®, a magnesium phosphate matrix, was developed by Argonne National Laboratory in the 1990s and has a struvite-K ($MgKPO_4 \cdot 6H_2O$) matrix. The reaction occurs at room temperature and is very exothermic, and waste forms typically require the addition of inert fillers. The resulting hardened monoliths typically have a low internal pH (about 10.5). Other non-hydraulic cements such as calcium sulfate cements and alkali-activated cements could also be selected.

Phosphate cements have potential to encapsulate reactive metal wastes without causing significant expansion and hydrogen generation as the result of corrosion. In addition, these cements generate fewer basic leachates and therefore may be more compatible with certain waste types (e.g., silicate glass waste forms). Individual ingredients or blends of ingredients for formulating magnesium phosphate cement reagents are commercially available from several sources. In general, phosphate cements are fast setting, have high compressive strengths, good durability, and can be used for waste streams containing transition metals and actinides, as these are stabilized as very low solubility phosphate compounds in the generated phosphate matrix; however, the rapid setting can lead to challenges in processing.

Geopolymers: If a non-crystalline SiO2 and Al2O3-rich material (either natural, manufactured, or industrial by-product similar to alkali-activated cement) can be activated with alkalis containing minimal calcium, an amorphous zeolite-type phase will be the predominant matrix phase (Duxson et al., 2007). Such materials are often described as geopolymers and present a distinct class of materials. Geopolymers used in nuclear waste are synthesized by combining a reactive aluminosilicate source, most commonly metakaolin (calcined kaolinite clay) or fly ash (product of coal-fired electrical power plants), with an aqueous sodium silicate solution (known as water glass) or potassium silicate solution, along with the waste to be conditioned (Kim et al., 2021; Ren et al., 2021; Liu et al., 2017).

The reactive aluminosilicate reacts through a polycondensation process under the high-pH conditions, which results in setting and hardening. The resulting matrix is rather versatile in terms of accommodating different waste components, which are either physically entrapped within the pore space (predominantly the case for anionic species) or sorbed onto the aluminosilicate surfaces. SIAL® is a waste form with a geopolymer matrix developed in the Slovak Republic and is currently used to immobilize/solidify radioactive liquids, sludges, and sludge resin mixtures from a nuclear power plant (Hill et al., 2015).

A.3 GROUT DEVELOPMENT SINCE 2019 AND UPDATE TO THE NDAA-3134 FEDERALLY FUNDED RESEARCH AND DEVELOPMENT CENTER REPORT/NEXT STEPS

The NDAA17 report highlighted several open areas of interest that should be noted in future analyses (Appendix C of SRNL-RP-2018-00687). The areas of further interest are provided in this section along with any updated information related to the topic that has been gathered since 2019.

A.3.1 Large Vault Concept

Section C.2.1.2 of the NDAA17 report suggested the use of a large vault at Hanford for LAW, similar to the SRS Saltstone Disposal Units (SDU), but noted: "*The potential improvements to the performance and economics would need to be evaluated quantitatively, which was beyond the scope of this assessment. A potential downside to SDUs is the inability to retrieve the waste form should an issue arise with the curing of a particular batch*."

The concept of the SDU-sized waste form at Hanford is evaluated in alternatives Grout 5A and 5B in Volume II, Appendix C, Section C.14 of this document. The computational analyses of reoxidation, the approach to retrievability, and other processes within an SDU-sized monolith at Hanford (referred to in this report as a grout disposal unit [GDU]), along with supporting experimental information, are also covered in Appendix C, Section C.14. In summary, the use of a large vault isolates more of the waste from environmental exposure due to the large volume to surface area ratio. In addition, GDU geometry would provide longer transport pathways compared with containerized waste forms greatly slowing release from the GDU and slowing the ingress of reactive environmental species (e.g., oxygen, CO_2). The result would be that the GDU may maintain the initial conditions of a majority of the waste form for extended timeframes. The primary uncertainty is the lack of an updated performance assessment (PA) for a GDU geometry at Hanford but could be based off of the SRS PA. It is believed that the GDU system would perform much better versus the individual containerized disposal for the reasons cited.

As discussed in the taxonomy evaluations, retrieval of a GDU is feasible but expensive. Placement of grout waste form containers within a GDU eases some of the potential retrieval challenges.

A.3.2 Adaptability to Waste Compositions

Section C.4.1 of the NDAA17 report highlighted an unaddressed issue of: "*Testing over a comprehensive range in LAW chemistry consistent with ranges anticipated in the feed vector. Westsik et al. (2013a) [PNNL-22747] did include a high sulfate LAW composition (which captures most of the feed vector range), but variations in other constituents should also be considered as should appropriate waste loadings*." The adaptability of grout waste forms to waste composition was assessed in the detailed analysis criteria taxonomy in Volume II, Appendix D, Section 3.1.3 of each alternative.

In summary, an analysis of the composition of the supplemental LAW projected feed against LAW grout testing to date strongly suggests that a single grout formulation can be used to immobilize a variable waste feed. In cases where the baseline formulation does not give desirable properties, there is experience in identifying successful substitute formulations to achieve the required performance. High confidence exists in the ability to adapt to waste composition.

Many elements can be involved in the hydration or polymeric reactions that produce the matrix of a grout waste form. The wide range of hydrated phases that are produced in the grout as a result are thus receptive to wide variations in waste composition resulting in minimal impact on the properties of the grout. As such, a single grout formulation can be used for a variable waste feed without the need for further formulation development.

To date, a wide range of LAW compositions have been tested using the Cast Stone formulation (PNNL-22747, *Supplemental Immobilization of Hanford Low-Activity Waste: Cast Stone Screening Tests*; Asmussen et al., 2018; VSL-21R5000-1). In the screening study of Cast Stone for LAW (PNNL-22747), several variations of LAW simulant were prepared to test the maximum concentrations of aluminum, sulfate, and phosphate. The results showed only minimal change in the performance of the solidified Cast Stone, and the results remained within the target properties. While other formulations could be used to improve processing and final properties, the Cast Stone test case demonstrates the adaptability to waste composition.

A comparison between the projected maximum concentrations of the main chemicals of interest in both the blended supplemental LAW treatment and direct-feed LAW (DFLAW) feed vectors against the tested LAW Cast Stone ranges is shown in Table A-1. With the similarity between the Cast Stone (47 wt% BFS, 45 wt% FA, 8 wt% OPC) and Saltstone (nominally 45 wt% BFS, 45 wt% FA, 10 wt% OPC but has a variable operating composition range) formulations, the maximum allowable concentrations in the salt waste immobilized with saltstone at SRS to date are also listed.

Table A-1. Comparison of Maximum Concentrations in the Projected Feed Compositions, Tested with Cast Stone, in Saltstone Salt Batches, and in Saltstone Waste Acceptance Criteria

Waste Constituent	Maximum Value (mol/L)				
	Supplemental LAW	DFLAW	Tested	Saltstone Salt Batches	Saltstone Waste Acceptance Criteria
Sodium	7.69	6.13	7.80	7.51	-
Hydroxide	-	2.00	2.43	2.75	11.47
Nitrate	3.05	2.76	3.90	2.82	8.27
Nitrite	1.19	0.99	1.51	0.98	5.63
Phosphate	0.03	0.04	0.08	0.01	0.37
Aluminum	0.98	0.16	0.87	0.39	5.23
Carbonate	0.62	-	0.74	0.32	2.42
Chromium	0.07	0.01	0.08	0.00	0.03
Sulfate	0.18	0.08	0.23	0.13	0.72
Fluoride	0.13	0.09	0.09	-	0.26
Chloride	0.10	0.19	0.14	-	0.27
Potassium	0.15	0.26	0.22	-	0.94

DFLAW = direct-feed low-activity waste. LAW = low-activity waste.

The only waste constituents where the tested concentration to date is lower than the projected supplemental LAW treatment feed vector concentration are aluminum and fluoride, although the differences are less than a factor of 2. The Saltstone bounding waste acceptance criteria concentrations, developed based on historical testing efforts (X-SD-Z-00004, *Waste Acceptance Criteria for Transfers to the Z-Area Saltstone Production Facility During Salt Disposition Integration (SDI)*), were established to show upper bounding concentrations where Saltstone will still have properties to meet disposal waste acceptance criteria. The Saltstone waste acceptance criteria concentrations are much larger than either the projected or tested supplemental LAW concentrations to date. This comparison provides a basis for the statement that a grout waste form can adapt to a range of waste composition.

If the waste feed changes beyond any waste acceptance criteria for a grout treatment facility, an alteration to the formulation can be made. An example of this scenario was in the qualification of grout waste forms for liquid secondary wastes generated at the Hanford Effluent Treatment Facility (ETF). This waste stream was projected to have a high sulfate content that was orders of magnitude higher than the concentration in LAW. When the Cast Stone formulation was used to immobilize this waste stream, solidification challenges were encountered due to the excessively high sulfate content. However, work at the 222-S Laboratory recommended the use of a formulation containing hydrated lime, BFS, and OPC to react the excess sulfate (RPP-RPT-31077, *Effluent Treatment Facility Waste Stream Monolith Testing Phase* II). Testing of this formulation at Pacific Northwest National Laboratory (PNNL) and SRNL demonstrated acceptable performance, including enhanced technetium retention (PNNL-25129, *Liquid Secondary Waste Grout Formulation and Waste Form Qualification*; SRNL-STI-2015-00685, *Liquid Secondary Waste: Waste Form Formulation and Qualification*; Bourchy et al., 2022). This effort to address the sulfate content was a successful demonstration of adapting a grout formulation to address changes in waste composition.

A.3.3 Variation in Dry Mix Components and Substitutions

Section C.4.1 of the NDAA17 report noted a gap of: "*Testing of dry mix constituents in a manner to elucidate causes in observed differences in effective diffusion coefficients. This is particularly true for technetium, which showed a 100x variation in the screening tests. Understanding the cause of this variability would allow optimization of mix designs for maximum retention*."

The NDAA17 report (SRNL-RP-2018-00687) also highlighted a gap in alternate formulations being tested for LAW, stating: "*Testing of a range of alternative substitutes for mix design components with uncertain future availability (should be performed)*."

In summary, an analysis of available data did not identify definitive cause and effect relationships between dry-mix constituents and resultant contaminant effective diffusivities. Note that a 100× variation in D_{obs} corresponds to a 10× variation in release rate (release rate is proportional to the square root of D_{obs}) and variations of 10 – 100× or greater in release rates are not uncommon for glass waste forms. Recent work has been ongoing for LAW and other liquid wastes that has provided insight into alternative formulations and amendments/additives for enhanced retention of specific contaminants of concern. As such, there is high confidence that an effective and durable grout waste form can be designed for Hanford LAW.

An existing analysis of the variation in the properties of LAW Cast Stone is documented in PNNL-22747. Section 8 of PNNL-22747 covers a statistical analysis of the sample variables (simulant composition, dry material sources) against the measured properties of Cast Stone (leachability, plastic viscosity, heat generation). The summary of the statistical analysis found no consistent correlations between the variations in the dry reagents and resulting performance properties of Cast Stone. However, the analysis did allow a down-selection of regional BFS and FA sources.

The PNNL report summarized the findings as follows:

> "*The objective of the Cast Stone screening study was to identify which parameters (individually or in interactions) affect which Cast Stone properties. Ideally, some parameters would be identified as not affecting any of the more important properties that were statistically analyzed, so that those parameters could be removed from consideration for future Cast Stone optimization studies. However, as noted in the preceding discussions of Table 8-29 and Table 8-30 [of PNNL-22747], every parameter has individual as well as interaction effects for at least one property.*

This includes BFS, which was believed not to interact with other parameters during the test matrix development (see Appendix A [of PNNL-22747]). Even though parameters like BFS and Fly Ash have statistically significant individual and interactive effects, the test results and statistical analyses of those results provide a basis for choosing a source of BFS and a source of Fly Ash to eliminate one or both of those parameters from a future formulation optimization study. Further, the statistical analyses in this section provide a basis for choosing the simulants and ranges of the NaMol and MixRatio."

Recent work has also begun to evaluate the performance of alternate formulations and geopolymers for the immobilization of LAW. The work in VSL-21R5000-1 screened several formulations including an OPC/BFS/calcium aluminate cement, neutral salt activated slag, alkali silicate activated slag, and ultra-high performance concrete (both geopolymer and portland cement based). The results (set time, compressive strength, and leaching) varied by formulation but many of the alternatives have improved properties compared with Cast Stone, including lowering leachability of iodine and technetium. Further testing of these formulations is ongoing.

The current baseline formulation for Cast Stone is defined in RPP-RPT-26742, *Hanford Containerized Cast Stone Facility Task 1 – Process Testing and Development Final Test Report*. The Cast Stone formulation (47 wt% BFS, 45 wt% FA, 8 wt% OPC) was down selected in testing of four formulations (Table A-2). The formulations in the down-select were chosen based on previous work in the Hanford grout vault program and the Saltstone at SRS. Dry reagent formulations (DRF)-1 and DRF-3 were removed due to leaching of chromium and selenium as no BFS was present, while DRF-4 had marginally better chromium and selenium, but not as good as DRF-2. DRF-2 was then identified as the formulation to consider for a Cast Stone waste form.

Table A-2. Formulation Considered in the Selection of a Baseline Formulation for Supplemental Treatment of Low-Activity Waste

Component (wt%)	DRF-1	DRF-2 Cast Stone	DRF-3	DRF-4
Portland cement, Type I/II	44.90	8.16	41.84	20
Class F fly ash	42.86	44.90	39.78	66
Blast furnace slag, Grade 120	0	46.94	0	0
Attapulgite clay	5.10	0	11.22	14
Indian red pottery clay	7.14	0	7.14	0

Adapted from Table 6-1 of RPP-RPT-26742, 2005, *Hanford Containerized Cast Stone Facility Task 1 – Process Testing and Development Final Test Report*, Rev. 0, CH2M HILL Hanford Group, Inc., Richland, Washington.
DRF = dry reagent formulation.

Cast Stone has been the most common formulation tested to date related to Hanford LAW, with slight modification to include getters. More formulation development has been performed for secondary wastes that have evaluated hydrated-lime-based waste forms (PNNL-26443, *Updated Liquid Secondary Waste Grout Formulation and Preliminary Waste Form Qualification*, and PNNL-26570, *Effluent Management Facility Evaporator Bottoms: Waste Streams Formulation and Waste Form Qualification Testing*) and a series of geopolymers (PNNL-19122, and VSL-19R4630-1, *Formulation Development and Testing of Ammonia Tolerant Grout Formulation Development and Testing of Ammonia Tolerant Grout*). Recent work at Vitreous State Laboratory (VSL) of The Catholic University of America has evaluated a series of alternate formulations for Hanford LAW (VSL-21R5000-1). The formulations screened included an OPC-BFS-calcium aluminate cement-gypsum formulation, a neutral salt activated slag, an alkali silicate activated slag, a geopolymer ultrahigh performance concrete, and OPC ultrahigh performance concrete.

The results showed that five of the six formulations had improved rhenium observed diffusivity (D_{obs}) values (rhenium used as a surrogate for technetium) compared with the performance metric (PNNL-28992), three of the six formulations had improved iodine D_{obs} compared with the performance metric, five of the six formulations had better performance for nitrate than the performance metric. The formulations also had sufficient properties for bleed water, set time, and compressive strength measurements. The work highlighted the promise of alternative formulations to be designed for LAW to enhance processing and performance if required.

At the SRS, work has been ongoing to develop cement-free Saltstone where the OPC content of Saltstone is removed. Formulations of only BFS and FA have been successful in meeting RCRA requirements based on the results of the Toxicity Characteristic Leaching Procedure (SRNL-STI-2019-00702, *Saltstone Third Quarter Calendar Year 2019 (3QY19) Toxicity Characteristic Leaching Procedure (TCLP) Results*).

In the development of opportunistic immobilization options for secondary wastes, specifically the evaporator bottoms from the Effluent Management Facility, alternate formulations comprised of commercial mixes or OPC+BFS were shown to be successful for immobilizing this waste stream (PNNL-26750, *Effluent Management Facility Evaporator Bottoms: Waste Streams Formulation and Waste Form Qualification Testing*). The Effluent Management Facility evaporator bottom stream tested was similar to LAW due to the high pH and chemical makeup.

In summary, many variations of grout formulations can be used in the grout alternatives to meet performance or processing requirements.

A.3.4 Oxidation Rates

Section C.4.1 of the NDAA17 report highlighted a gap of "*Testing to assess rates of oxygen ingress into Cast Stone monoliths and its impact on technetium release rates*."

In summary, the changing redox state within a grouted waste form for secondary waste was considered in sensitivity cases in the Integrated Disposal Facility (IDF) PA (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*) and as a dynamic process in the SRS Saltstone PA (SRR-CWDA-2019-00001, *Performance Assessment for the Saltstone Disposal Facility at the Savannah River Site*). Other modeling efforts to represent oxygen ingress (or other key processes including carbonation) are ongoing, and experimentally a large-scale lysimeter study at Hanford will generate valuable data to better predict the rate of oxygen ingress in grout waste forms. There remains uncertainty in the rate of reoxidation of grout waste forms within the IDF, but this can be handled through the use of sensitivity cases in PA modeling.

The rate of reoxidation of a grout waste form is crucial to predicting the long-term behavior of grout waste forms containing redox sensitive elements (e.g., technetium, chromium). Within the IDF PA (RPP-RPT-59958), the impact of oxidizing/reducing conditions was evaluated for the liquid secondary and solid secondary grout waste forms; however, a primary LAW grout waste form was not included in the IDF PA. Reoxidation was one of the chemical degradation mechanisms considered in the IDF PA, which stated:

> "*The cementitious waste forms are expected to evolve and degrade over time as a result of various physio-chemical processes.… Chemical degradation includes the effects of carbonation, sulfate attack and oxidation that may alter the mobility of CoPCs [constituent of potential concern] in the cementitious waste form and/or lead to physical degradation. Aging of the waste form has been correlated with the amount of water that interacts with the waste form.*
>
> *The assessment of potential degradation mechanisms, described in SRNL-STI-2016-00175, Section 10, indicates that SSW [solid secondary waste] grout degradation from chemical attack can be expected to be minimal under IDF disposal conditions due to the limited amount of recharge pore volumes that are expected to be exchanged within the waste form…*

The associated enhanced migration of oxygen into the waste form is taken into account by assuming oxidizing conditions for redox-sensitive CoPCs. Oxidizing conditions are effectively modeled by specifying the sorption coefficients that are applicable under oxidizing conditions for the different CoPCs for the nominal case. As a result, the potential effects of degradation of the waste form have been neglected in the process modeling. However, sensitivity analyses described in Section 6 (of RPP-RPT-59958) evaluated the effect of aging by increasing the effective diffusion coefficient of the cementitious waste after 500 years, which is the same approach that was used for the analysis in the TC&WM [Tank Closure and Waste Management] EIS."

The base case in the IDF PA assumed oxidizing conditions for the waste forms. This was achieved through applying a low distribution coefficient (K_d) for the contaminants in the waste form based on values suggested in PNNL-25194, *Secondary Waste Cementitious Wasteform Data Package for the Integrated Disposal Facility Performance Assessment.* Two primary sensitivity cases were performed in which the waste form remained reducing for the entire disposal life of the waste forms and a second case where the waste form K_d values gradually changed from reducing to oxidizing from outer to inner portions of the waste form. The K_d stepped through a series of five oxidizing time steps (250, 500, 750, 1000, and 1250 years) and five cells (from the outermost cell to the innermost cell). The reducing case lowered technetium release by over three orders of magnitude but had a slight increase in iodine peak concentration. The varying K_d case slightly delayed the time of peak technetium concentration and led to an earlier iodine peak.

The SRS Saltstone PA also calculates reoxidation rates as a moving front through the SDU monoliths; however, a shrinking core model is used in the SRS PA (SRNL-STI-2009-00473, *Geochemical Data Package for Performance Assessment Calculations Related to the Savannah River Site*). A shrinking core model is a less complex modeling approach than thermodynamic or reactive transport models. The shrinking core model assumes O_2 can enter the waste through water diffusing through the waste form and consuming the reduction capacity (slag) encountered in a fast reaction. This approach has agreed well with spectroscopic evidence of reoxidation (Lukens et al., 2005). Contradictory evidence also exists in samples that have been exposed to air, as air transport of O_2 is ignored in the SRS shrinking core model as the SDUs are saturated. Understanding and predicting the combined effect of air and liquid transport of O_2 in cementitious waste forms is still an open area of development and would refine projections of the maintenance of reducing conditions within waste forms. A waste form larger in size would have a slower rate of re-oxidation as the pathway for O_2 to reach the entire waste form would be far longer. Mitigation can be used by increasing the reduction capacity through increased slag content or additives (e.g., iron). Volume II, Appendix E, provides additional information.

The assessment of reoxidation rates of grout to date have been supported experimentally in laboratory and sediment tests, although not Hanford-specific. In 2018, a large-scale field lysimeter test was initiated at the Hanford Site (PNNL-27394, *Field-Scale Lysimeter Studies of Low-Activity Waste Form Degradation*) to evaluate the degradation of glass and grout waste forms in the most realistic disposal conditions to the IDF. The lysimeter test includes grout waste forms prepared with simulated LAW and liquid secondary wastes. The large forms emplaced in the IDF backfill sediment will be irrigated at different rates for several years. The liquid and gas moving through the lysimeter cell and past the waste forms are being monitored continuously. Upon excavation, the waste forms will be ideal test cases for the measurement of reoxidation rates within the Hanford subsurface.

Additional work at Vanderbilt University has focused on the individual and simultaneous aging processes of drying, carbonation and oxidation, and the impacts of aging on leaching from Cast Stone (Zhang, 2021; Zhang et al., 2021; Zhang et al., 2022; Chen et al., 2021; Chen et al., 2022). This research has developed a series of reactive transport models used to estimate the depths of carbonation and oxidation during pre-closure and post-closure scenarios and then estimate the fractional cumulative release of ^{99}Tc, ^{129}I, and other constituents of potential concern over time intervals up to 10,000 years.

A representative mineral and parameter assemblage for Cast Stone was used to develop and verify a geochemical speciation model of grouted material under oxic and anoxic environments. The mineral assemblage and geochemical speciation model supported in a reactive mass transport model, along with data from the IDF PA and hydraulic modeling of the IDF waste package, to provide an estimation of the releases of ^{99}Tc, ^{129}I, and other constituents of potential concern from the grout waste form during operational periods including pre-closure (i.e., IDF exposed to atmospheric conditions during filling), early post-closure (i.e., IDF exposed to subsurface environments with intact cap), and late post-closure (i.e., buried IDF exposed to increased infiltration because of the degradation of cap). Model parameters were developed from experimental data on Cast Stone material created with non-radioactive constituents and verified using ^{99}Tc leaching data from PNNL (PNNL-25129). Results indicate good retention for ^{99}Tc in Cast Stone prior to environmental exposure; however, oxidation of Cast Stone increased the ^{99}Tc release rate by over one order-of-magnitude. Approximately 67% of oxidation and 41% of carbonation occur during the pre-closure period, indicating that impacts can be substantially decreased by appropriate controls during IDF operation. While ^{99}Tc retention is maximized under chemical reducing conditions, retention of ^{129}I by precipitation with silver-based getters primarily occurs under oxidizing conditions. The presence of both ^{99}Tc and ^{129}I suggest the need for either an irreversible ^{129}I getters during initial grout waste form curing (i.e., chemical stabilization under initially oxidizing conditions leading to development of reducing conditions during curing) or a spatial zonation of ^{99}Tc and ^{129}I retention mechanisms. These results point to the benefits of larger waste form geometries that minimize surface area, slowing oxidation, and, in turn, further slowing the release of ^{99}Tc and other redox-sensitive contaminants. Volume II, Appendix E provides additional information.

A.3.5 Iodine Getters

Section C.4.1 of SRNL-RP-2018-00687 described a gap of "*Testing to assess the effectiveness of iodine getters in conjunction with Cast Stone formulations over a comprehensive range in LAW chemistry consistent with ranges anticipated in the feed vector. Testing to identify other potential iodine getter formulations/materials (e.g., bismuth-based as Ag is a RCRA listed metal).*"

In summary, data sets exist showing the efficacy of iodine getters in LAW Cast Stone. The most important factor in success of an iodine getter is the ratio between the silver added and the amount of total halides present. Alternatives to silver have been proposed and are currently under study. The uncertainty around iodine is further discussed in Volume II, Appendix E, Section E.3.1.1.

The concept of an iodine getter within grout is based on the fact that rate of iodide (I^-) and iodate (IO_3^-) release from grout waste forms are similar to that of other "mobile" constituents, such as sodium and nitrate. However, iodide and iodate have several ionic compound forms with low solubility (e.g., silver iodide, AgI, with a K_{sp} of 8×10^{-17}) and some ion-exchange materials have been demonstrated for iodine sequestration (Cordova et al., 2020). Testing of the incorporation of silver zeolites (AgZ) into grout have shown significant reduction in the amount of iodine released while yielding minimal impact on overall grout physical properties up to 30 vol% (Yamagata et al., 2022). Several laboratory studies have been performed to investigate the ability of getters to retain iodide in grout waste forms, including work since the NDAA17 study (SRNL-RP-2018-00687). These examples can be grouped into test cases where the getter was successful in lowering iodine release and cases where not enough getter was added.

A.3.5.1 Successful Demonstration of Iodine Getters

Several examples demonstrate an iodine getter, or iodine-loaded material, being incorporated into a grout waste form and leading to slowed iodine release. From the examples below, a trend is apparent in which the ratio of Ag to iodine (or total halides) is crucial in ensuring optimum getter performance. Original work at Hanford related to the immobilization of iodine-loaded sorbents in grout included a comparison between (1) iodine-loaded AgZ, (2) $Ba(IO_3)$ in cement ($BaIO_3$ cement being the baseline at the time for the byproduct of the Mercurex process), and (3) AgI directly added to the grout.

Iodine was observed to be released an order of magnitude slower from the AgZ-grout compared with the barium-modified samples, while the directly added AgI had the lowest release (PNL-4045, *Selection of a Form for Fixation of Iodine-129*).

The work performed in RPP-RPT-26742 carried out studies of two natural getters (bone char and "will form" a calcium phosphate product expected to have a hydroxyapatite like structure) and two silver-containing compounds (silver zeolite and silver mordenite) added to Cast Stone and made using a highly alkaline secondary waste (pH = 13.5). All four getters had no measurable iodine in the leachate in a 19-day leach test (ANS 16.1) at the lowest iodine loading (~4 mg/L iodide) and varying the getter loading between 1 wt% and 5 wt%. However, measurable iodine in the leachate was found when the iodine concentration was increased (~8 mg/L and 17 mg/L) with 5 wt% getter loading of the natural getters and silver mordenite. The silver zeolite still had no measurable iodine release at the higher concentrations. The Ag:I molar ratio in the grouts ranged between ~60 to ~95.

The work in SRNL-STI-2016-00619 documented the immobilization of a Tank 50 waste sample from SRS that was adjusted to be compositionally comparable to Hanford LAW. A sample of real waste from Tank 50 was spiked with iodide (85 mg/L) and Cast Stone samples were prepared with and without AgZ (11 wt%). This higher loading of AgZ led to a near three order-of-magnitude reduction in iodide diffusivity (using EPA Method 1315) compared with the getter free system. The Ag:I molar ratio was 10, and the amount of Ag added by the getter was equal to the total halide molar content of the liquid waste (I, Cl, and F).

PNNL-26443 discussed the use of iodine getters in the preparation of a liquid secondary waste (pH = 6) with a hydrated lime-based formulation (20 wt% hydrated lime, 35 wt% Class F FA, 45 wt% BFS). In this work, the diffusivity of iodide was decreased by close to four orders-of-magnitude using EPA Method 1315. The Ag:I molar ratio was ~425 and the Ag:halide molar ratio was ~100.

Yamagata et al. (2022) placed iodide-loaded silver mordenite into a pair of formulations: one containing BFS and one without BFS. In EPA Method 1315 leach testing, these formulations both measured diffusivities that were orders of magnitude lower than the non-zeolite containing control samples. The molar ratio of Ag:I was ~2700. Although the BFS-containing samples had measurable iodine in the leachate at longer leaching times (>40 days), the BFS-free samples did not have any measurable iodine in the leachates. This response was likely due to some destabilization of the AgI from the BFS. This work also provided evidence to support the mechanism of iodine retention, in which the AgZ was observed to form a layer of silver around the particle, which could serve as a barrier to iodine transport.

A.3.5.2 Unsuccessful Iodine Getters Tests

Two properties can influence AgI (or other iodide/iodate salts) stability within grout waste forms: the alkalinity of the environment and the interference of redox species (e.g., sulfide). Asmussen et al. (2017) monitored the dissolution of AgI in solutions of varying pH and with the addition of sulfide sources (as an example redox species). This study showed that AgI can be destabilized in alkaline or reducing systems. However, as reducing systems become oxidized with time, conditions become more favorable for efficacy of an iodine getter. The following are examples of test cases where iodine getters were not successful, mainly due to insufficient Ag:I ratios.

Asmussen et al. (2016) screened a series of materials, including AgZ, argentite (Ag_2S), layered bismuth hydroxide, and a silver-impregnated carbon for removal of iodide from simulated LAW. The two best performing materials from that study, AgZ and argentite, were used as getters in Cast Stone testing (PNNL-25577, *Getter Incorporation into Cast Stone and Solid State Characterizations*). When the iodide-loaded getters were placed in the Cast Stone, there was no improvement in release in EPA Method 1315 leach testing. The Ag:I molar ratio used was between 85 and 600; however, the Ag:halide ratio ranged from 0.03 to 0.22, which indicates an insufficient amount of Ag was present in the samples.

The work in VSL-19R4630-1 tested three iodine getters (two proprietary getters and a AgZ) in a sulfate-activated slag waste form used to immobilize a high ammonium, high sulfate waste stream. The sulfate-activated slag formulation was designed to lower ammonia generation during processing. In this study the getter Ag:I molar ratio was <10 and no improvement was observed in EPA Method 1315 leach testing. However, chloride was also present in the simulant, which means that the Ag:halide ratio was much lower than 10.

AgZ was also tested as a getter in a phosphate bonded ceramic (Ceramicrete) and an alkali activated geopolymer (DuraLith), PNNL-20632, *Waste Acceptance Testing of Secondary Waste Forms: Cast Stone, Ceramicrete and DuraLith*. In this study, AgZ was added at 1 wt% of the overall mix for both waste forms. This loading equated to an Ag:I molar ratio of 830 for the Ceramicrete and 922 for the DuraLith. However, the simulant used had a high chloride content and the Ag:halide ratio was 0.2 for both formulations, meaning there was insufficient Ag to control iodine release. As expected, there was little to no improvement in iodine release in leach testing with EPA Method 1315, ANS 16.1 and ASTM C1308.

Work by VSL (VSL-21R5000-1) included an evaluation of calcined hydrotalcite and AgZ as iodine getters in a neutral salt-activated slag geopolymer waste form for LAW. The inclusion of either calcined hydrotalcite or AgZ improved the iodine leachability by an order-of-magnitude when using a 1 M Na LAW simulant (using EPA Method 1315). However, the calcined hydrotalcite did not improve iodine retention in a waste form using a 5.6 M Na LAW simulant. The simulant used for the samples had an unrealistically high concentration of iodine of 1 g/kg (1250 mg/L). In the case of the AgZ getter, the Ag:I molar ratio was ~10 and the Ag:halide molar ratio was ~5.

In summary, recent work has highlighted the importance of the ratio of Ag:I and Ag:halide in ensuring improved iodine retention for on-site disposal scenarios (improved iodine retention is not required in off-site disposal options). Alternates to silver have been postulated but not tested to date (e.g., bismuth). The optimum ratio of silver (or other active species) to iodine (or total halides) is not yet defined to ensure strong iodine retention and to also minimize costs.

In the current evaluation summarized in this report, a conservative assumption is made that an Ag-based iodine getter loading of 5 wt% is required in the grout waste forms, but it is projected that a lower amount (based on the Ag:halide ratio) will be equally successful and improve economics. Efforts to optimize the required Ag:halide ratio and evaluate silver substitutes is currently ongoing in 2022.

A.3.6 Land Disposal Restriction Organics

The NDAA17 report (SRNL-RP-2018-00687) identified a technical gap related to the role of Land Disposal Restriction (LDR) organics in waste acceptance of grouted waste forms and potential impacts on treatment processes on the resulting waste stream: "*Testing to assess the potential impact of the process to address LDR organics on the performance of the grouted waste form*" and "*The process to destroy LDR organics impacts the performance of the grouted waste form, which may be a particular concern for technetium. This risk is addressed above in the recommendations for additional testing in Section C.4.1 [of SRNL-RP-2018-00687]. This risk applies to IDF only.*"

In summary, extensive work has been ongoing to better understand the extent and magnitude of LDR organics within the Hanford tank wastes and ways to remediate organics present prior to immobilization (e.g., evaporation, oxidation). The LDR organics, at the concentrations projected, are not anticipated to impact the properties of the grout; however, there is limited direct data on the influence of the major organics in Hanford waste on candidate grout waste forms. Disposal performance of a grouted waste form related to LDR organics is based on total concentration in the waste form. A summary of the recent works related to LDR organics at Hanford since the NDAA17 report is provided. The main uncertainty around LDR organics remains in the quantification and potential need for treatment, but the knowledge base has grown since the NDAA17 report.

There have been several efforts since the NDAA17 report (SRNL-RP-2018-00687) related to the understanding and management of LDR organics in Hanford LAW. The handling of LDR organics was recently discussed in SRNL-STI-2021-00453, *Potential for Evaporation and In-situ Reaction of Organic Compounds in Hanford Supplemental LAW*: "*Regulated organic species under the Environmental Protection Agency's Resource Conservation and Recovery Act (RCRA) LDR program in 40 Code of Federal Regulations (CFR) Part 268 are important to understand because of the dilution prohibition in 40 CFR 268.3. EPA established the dilution prohibition to prevent owner and operators of hazardous waste management units from intentionally diluting waste to avoid treatment. EPA typically requires that regulated organic species are "removed" or "destroyed" to meet the LDR program requirements. EPA also does not regard stabilization through using cementitious reagents to provide adequate treatment for organics but has provided some guidance that stabilization of low concentration organics may be acceptable.*"

A.3.6.1 Assessment of the Extent and Magnitude of Land Disposal Restrictions Organics in Tank Waste

Staff at the 222-S Laboratory generated an evaluation of the LDR organic content of wastes in the Hanford double-shell tanks (DST) (RPP-RPT-61301, *Current Chemical Knowledge Concerning Organic Chemicals in Hanford Double Shell Tank Waste Supernatant* [Rev. 1]). The objective of this report was to provide a technical basis to aid in the characterization of organic compounds in the tank waste feed. The goal of the evaluation was to reduce the number of analytical targets for constituents of concern when evaluating against LDR regulations. The constituents of concern evaluated were the volatile organic compounds (VOC), semivolatile organic compounds (SVOC), and polychlorinated biphenyls (PCB) that are included in the list of 207 regulated LDR organic constituents developed from the DST Part A permit application (DOE, 2009) and associated Underlying Hazardous Constituents from 40 CFR 268.48, "Universal Treatment Standards" (SRNL-STI-2020-00228, *Evaluation of Technologies for Enhancing Grout for Immobilizing Hanford Supplemental Low-Activity Waste (SLAW)*). The current chemical knowledge used in the evaluation included input knowledge (e.g., RPP-21854, *Occurrence and Chemistry of Organic Compounds in Hanford Site Waste Tanks*), solubility, chemical reactions, headspace vapors (e.g., PNNL-13366, *A Survey of Vapors in the Headspaces of Single-Shell Waste Tanks*), mass balance, historical analyses from the Tank Waste Information System (TWINS), and Aroclors (PCB) solubilities. RPP-RPT-61301 concluded that current chemical knowledge indicates there were 31 regulated organic compounds used on the Hanford Site. Chemical reactivity analysis suggested that one or more compounds could be formed within the waste. From historical analyses, 22 constituents of the 126 analyzed were detected with concentrations higher than their corresponding action level, specified in RPP-RPT-61301. Only eight of these chemicals were detected more than 10 times in the waste. This report makes a strong case for the concept that current chemical knowledge can effectively be employed to eliminate the consideration of many compounds of regulatory concern and minimize the requirements for analytical work to meet the regulatory requirements and data quality objectives.

The use of process knowledge to screen the list of 207 LDR organic compounds associated with the Part A waste codes and underlying hazardous constituents for the DSTs and SSTs, to a list of compounds that can be considered as potentially present, was further developed in the analysis reported in RPP-RPT-63493, *Tank Waste LDR Organics Data Summary for Sample-and-Send*. In this work, WRPS staff defined and applied seven decision rules to screen out compounds that have no historical or current support for being present in Hanford tank waste. Compounds were identified as being potentially present in tank waste if the compound:

1. Is a Hanford tank farms F001–F005 constituent, or
2. Is a RCRA Part A "D" code: D018, D019, D022, D028, D029, D030, D033, D034, D035, D036, D038, D039, D040, D041, D043, or

3. Was used at Hanford, including identified components in commercial products (prior to May 8, 1992), or
4. Has been detected in the single-shell tanks (SST) or DST samples (past and future), or
5. Was not included in past analytical methods but can be reasonable expected to be present, or
6. Is a decomposition reaction end product formed in the waste, or
7. Is identified on an LDR notification form from past (and future) transfers into the DSTs, and:
    a. Was detected at or above the LDR wastewater standard, or
    b. Has no analytical data to indicate concentration, or
    c. Process knowledge cannot be developed to support the constituent is not in the waste when reported as "<MDL" (method detection limit), but the MDL is greater than the LDR wastewater standard.

The application of the seven decision rules eliminates 75 compounds from the list of 207 (RPP-RPT-63493). The remaining 132 compounds are considered as potentially present and are the target for future tank waste characterization efforts.

In the process of completing this screening effort, WRPS staff reviewed the available data in TWINS for the 207 LDR organic compounds to determine the extent to which these compounds are distributed in tank waste (RPP-RPT-64064, *Distribution of LDR Organic Compounds in Hanford Tanks Waste and The Implications to LAW Treatment by Cementitious Solidification/Stabilization*). Particular emphasis was placed on:

1. Quantifying the amount of LDR organic data available for individual tanks and waste phases
2. Defining the magnitude and extent of the distribution of LDR organic compounds in Hanford tank waste
3. Estimating the concentrations for LDR organics in retrieved LAW and a cementitious waste form made from the LAW
4. Assessing if the estimated concentrations in the hypothetical cementitious waste form would exceed the non-wastewater standards for disposal in a near-surface mixed low-level waste landfill.

Results from this data screening effort showed that within the historic data for the 177 DSTs and SSTs that originally stored Hanford reprocessing waste, approximately 27,091 individual entries[1] for LDR organics are derived from approximately 1,511 laboratory samples generated in a little over 1,000 historic sampling events. Only 1,199 of the 27,091 entries represent values above the corresponding detection limit. For the current 156 unretrieved tanks, 93 have some LDR organics data in TWINS, but only 31 have LDR organics data other than for PCBs. Eleven of the 31 tanks with non-PCB results are SSTs and the remaining 20 are DSTs. The five compounds with the highest detection frequencies are acetone (65%), acetonitrile (42%), n-butyl alcohol (39%), 2-butanone (38%), and bis(2-ethylhexyl)phthalate (34%).

46 sample results from liquid samples and 19 from solid samples exceed the non-wastewater standard. Some exceedances represent multiple samples from the same sampling event and if only one exceedance is counted for a unique compound/tank number/sampling event, only 18 exceedances are from liquid samples and 15 from solid samples. The exceedances are confined to the 11 compounds, with n-butyl alcohol, n-nitrosodimethylamine, and n-nitrosomorpholine being most prevalent in liquid samples and the composite PCB parameter (all Aroclors) being the most prevalent in solid samples.

[1] An entry considers both detected and non-detected values.

Assuming the historic liquid samples that exceeded a non-wastewater standard are directly retrieved, altered to produce a 5.5 M sodium solution (without altering the mass of the organics), and immobilized into a cementitious final waste form results in nine unique liquid sampling events from seven tanks (AN-107, AP-104, AP-107, AP-108, AW-102, AW-104, and AW-106) that are predicted to produce a solidified/stabilized final waste form that exceeds the non-wastewater standard for an LDR organic. Note that these tanks are DSTs that are most likely to be retrieved and processed during DFLAW operations through the Waste Treatment and Immobilization Plant (WTP). N-butyl alcohol is the exceeding compound in eight of the nine cases and n-nitrosomorpholine in one case. No case has more than one exceeding compound.

For the solid samples that show a concentration above a non-wastewater standard, six of the 19 solid samples with in-tank concentrations above the non-wastewater standard are predicted to create a final waste form that also exceeds the non-wastewater standard. Five of the six samples are associated with PCBs and one with toluene. All of the calculated PCB concentrations in retrieved waste are well above the water solubility for PCBs, which suggests these compounds would not be present at these levels as a dissolved species. Rather, PCBs would be associated with either an organic phase or absorbed to the retrieved solids. In either case, the undissolved PCBs would be removed by the filter system associated with the tank-side cesium removal (TSCR) process. If only dissolved PCBs are present in the liquid sent for solidification/stabilization in a cementitious matrix, the final concentration in the waste form would be below the PCB non-wastewater standard of 10 mg/L due to the solubility limits.

A.3.6.2 Regulatory and Processing Considerations for Grouting Low-Activity Waste

An expert team evaluation of technologies that could be implemented to target key species (technetium, iodine, NO_3/NO_2, LDR organics) in Hanford LAW was performed in 2020 (SRNL-STI-2020-00228). The report released by the expert team included a summary section on the classification of LDR organics and relevance to Hanford LAW that expanded on the information in the NDAA17 report (SRNL-RP-2018-00687).

The expert panel presented two general approaches that could meet regulatory concentration limits for RCRA LDR organics. The first approach, termed sample-and-send, would rely on direct sampling of the retrieved and treated waste, for LDR organics assuming LDR concentrations limits were met, sending the material to supplemental treatment (this sample and send approach is covered as alternative Grout 1D in this report for technetium and iodine). The second approach identified was the use of a pretreatment process (e.g., evaporation, oxidation) before sending the LAW to supplemental treatment. Note that later work has recognized that the idea of "sample-and-send" is applicable to a three-option treatment strategy where retrieved and staged waste is sampled and, depending on the LDR organic content, is:

1. Sent directly for cementitious stabilization/solidification if the organic content is low enough to produce a final waste form that meets LDR requirements, or
2. Sent for additional organic treatment and then for cementitious stabilization/solidification if the additional treatment will produce a final waste form that meets LDR requirements, or
3. Sent for vitrification if organic content in a final grouted waste form will not meet LDR requirements.

The use of evaporation to volatilize and separate organics from the LAW was identified as the most promising. Other methods evaluated that were deemed less likely to be successful included the use of permanganate for chemical oxidation (could cause precipitation of solids), hypochlorite oxidation (interference with nitrate and production of chlorinated organics), ozone destruction (nitrate interference), electron beam destruction (impractical for deployment), and activated carbon sorption (competition). Full descriptions and associated references for these processes are provided in SRNL-STI-2020-00228.

Following the expert team evaluation, Washington River Protection Solutions, LLC (WRPS) has further refined the sample-and-send regulatory strategy to account for the potential need to address the requirements of the dilution prohibition by first compiling volatility, radiolysis, and reactivity information to confirm that "treatment" for many LDR organics has already taken place through either in-situ decomposition reactions during storage (destruction) and through historical evaporation campaigns (removal) (RPP-RPT-63493). Using this supporting information, LDR organics shown to have been destroyed or removed from Hanford tank waste would not be a concern for the dilution prohibition. Those compounds for which there is no identified historical "destruction" and "removal" mechanism may need to be part of an LDR treatment variance. Whether an LDR treatment variance is pursued by DOE for LDR organics is beyond the scope of this evaluation. If DOE chooses to include a treatment step for LDR organics in an implemented sample-and-send strategy prior to grouting to demonstrate no "impermissible dilution" occurs, then an LDR treatment variance may not be required.

Decisions on compounds that have removal or destruction mechanisms are supported by work at SRNL that has (1) tested the impacts of evaporation (using a laboratory vacuum evaporator) on organics in LAW, and (2) compiled published reactivity, volatility, and solubility information. In FY 2020, SRNL conducted evaporator testing using a LAW simulant spiked with target organic compounds (acetone, acetophenone, butanol, methanol, and pyridine) to identify a lower volatility limit, above which compounds would have been removed by evaporation. The test used a laboratory vacuum distillation system operating under conditions similar to the Hanford 242-A Evaporator (60 ±5 torr absolute, which resulted in an initial boiling point of the liquid around 44°C). This work demonstrated that >98% of the five organic chemicals investigated partitioned to the overhead stream, and no significant reactions were observed between the organic species and the LAW. The experimental results were supported by thermodynamic equilibrium modeling using OLI Studio (OLI Systems, Inc.). These results suggest that compounds that do not ionize below pH 13, and have a volatility (expressed as the Henry's Law vapor-liquid partition coefficient) greater than or equal to methanol, can be expected to have been removed by historical evaporation campaigns.

In FY 2021, SRNL continued this effort by completing a thorough review of published chemical property data for 73 of the 132 possibly present LDR organic compounds to identify aqueous Henry's Law coefficients and pK_a values (SRNL-STI-2021-00453). Since LAW has a pH at or above 13, the latter information is needed to identify species that ionize below pH 13 and so would not be as volatile as indicated by a typical published Henry's Law coefficient. This work also confirmed through OLI modeling that volatility increases with salt content, and so Henry's Law coefficients measured in water are an under prediction of volatility in LAW. Finally, the FY 2021 SRNL report included an initial assessment of in situ decomposition for the 73 compounds by reviewing and compiling published information on rates of alkaline hydrolysis.

Follow-on work at SRNL in FY 2022 extended the FY 2021 data compilation effort to include solubility, reactivity, radiolysis, and pK_a values for all 207 LDR organic compounds associated with Hanford tank waste. In addition, since the FY 2020 evaporator experiments demonstrated removal of the five organic compounds tested, laboratory work in FY 2022 measured the impacts of both atmospheric and vacuum evaporation on less volatile compounds. Results showed that compounds with Henry's Law coefficient at least 186× below that of methanol (and that are not present as charged species) are removed from LAW by atmospheric evaporation. Vacuum evaporation was only tested with compounds with Henry's coefficients up to 9.6× below that of methanol, but since vacuum evaporation achieved greater removal fractions than atmospheric evaporation for all compounds tested under both conditions, this method is assumed to likely remove n-nitrosomorpholine (Henry's coefficient 186× below methanol). This assumption is planned to be tested in FY 2023 work.

Permanganate and peroxide oxidation tests were also conducted in FY 2022 to assess the potential to use chemical oxidation to remove more recalcitrant compounds. Results at 60°C demonstrated that phenol, 4-chloroaniline, ortho-cresol, 4,6-dinitrocresol, and n-nitrosomorpholine appear to be treatable in the LAW simulant even in the presence of high concentrations of nitrite and the organic acids acetate, formate, glycolate, and oxalate. In contrast, n-nitrosodipropylamine, 2,4,6-trichlorophenol, and phthalate appear to be more refractory. Oxidation testing at 25°C (6-hour exposure) with permanganate showed generally increased destruction of spiked organics including phthalate but apparent reduced effectiveness against n-nitrosomorpholine. In contract, hydrogen peroxide showed little ability to oxidize organics in the LAW simulant. Additional work is planned for FY 2023 to better define the compounds that can be oxidized by permanganate. Testing efforts will focus on the LDR organic compounds most prevalent in tank waste samples at elevated concentrations, particularly those that cannot be removed by evaporation.

The data provided by the FY 2020 through FY 2022 work at SRNL has been applied by WRPS to evaluate the potential for historic removal (by evaporation) and destruction (by in situ decomposition) of the 132 potentially present LDR organic compounds (RPT-RPT-63493). This work demonstrated 109 of these compounds are predicted to be removed by evaporation and eight of the remaining 23 compounds are predicted to be susceptible to in-situ decomposition. Five of the remaining 15 compounds have a water solubility below the assumed waste acceptance criteria[2,3] for cementitious stabilization. The remaining 10 compounds that are soluble above the assumed waste acceptance criteria are those that may require a treatment variance if the issue of the dilution prohibition cannot be resolved by other means such as (1) demonstrating that previous storage activities can be considered as "aggregation of wastes preceding legitimate central treatment" (55 FR 22664-22667, "The Dilution Prohibition as it Applies to Centralized Treatment") and (2) recognizing the volume increase that occurs during grouting as a necessary part of the process to treat a waste (54 FR 48494, "Determining When Dilution Is Permissible").

The need for a treatment variance also must take into account (1) the concentration of the LDR organic in the tank waste and its associated process knowledge, and (2) whether there is a known pretreatment step that is capable treating or removing the LDR organic in Hanford tank waste. If the LDR organic concentration exceeds LDR treatment standards or the waste acceptance criteria or if pretreatment is either inappropriate or not achievable (the two criteria for a treatment variance in 40 CFR 268.44(h)), the LDR treatment variance petition would include the LDR organics to avoid the addition of a pretreatment process.

A.3.6.3 Analytical Considerations

Analysis of the organics in Hanford waste analysis is needed to better quantify the organics present and support grout immobilization if implemented (e.g., prepare the shipment documentation before immobilization). Organic analysis may also be needed for on-site transfer documentation (e.g., 222-S Laboratory 219-S Waste Handling Facility to SY Farm).

Current 222-S Laboratory volatile organic analyte (VOA) and semivolatile organic analytes (SVOA) methods are capable of analyzing 91 of the 132 potentially present LDR compounds; however, many of the reporting limits are greater than the corresponding wastewater standard.[4] The laboratory has recently evaluated the ability to add additional analytes to their current methods and have indicated that all but four of the 132 could potentially be included in the VOA and SVOA methods (RPP-RPT-63493).

[2] The assumed waste acceptance criteria are equal to the highest concentration of an LDR organic in LAW that produces a final grouted waste form that meets the corresponding non-wastewater standard.

[3] Wastewater standard concentrations are concentration-based in the liquid, while non-wastewater standard concentrations are on a mass basis and are typically larger. Wastewaters are defined as waters that contain less than 1 wt% total organic carbon and less than 1 wt% total suspended solids. Non-wastewaters are wastes that exceed the wastewater criteria. Solidified/stabilized LAW is a non-wastewater.

[4] Establishing analytical methods capable of measuring at the wastewater standard is currently preferred to support manifesting the waste in case the material is shipped offsite for treatment.

The four compounds that are not applicable to these methods are the decomposition products phthalic acid and methanol and two compounds "reasonably expected to be present" (2,4,5-trichlorophenoxyacetic acid/2,4,5-T and 2,4-dimethylaniline). Staff at the 222-S Laboratory are currently evaluating other methods to quantify these compounds.

In addition to extending the ability of the analytical laboratory to measure all of the 132 potentially present compounds using current methods, recent work has been undertaken to develop alternate analytical techniques that can lower detection limits to the desired level. Work at the Hanford 222-S Laboratory has evaluated the potential for using stir bar sorptive extraction and thin film solid phase microextraction methods in an attempt to lower the detection limits for organic compounds in Hanford tank waste to below wastewater standards (RPP-RPT-63952, *Analysis of Organic Chemicals in Hanford Tank Waste Simulant by Stir Bar Sorptive Extraction*). In FY 2022, the efficiencies of the extraction of 131 VOC and SVOCs from tank waste simulants were evaluated with the methods giving promising results in lowering detection limits. Further development work of the techniques are ongoing.

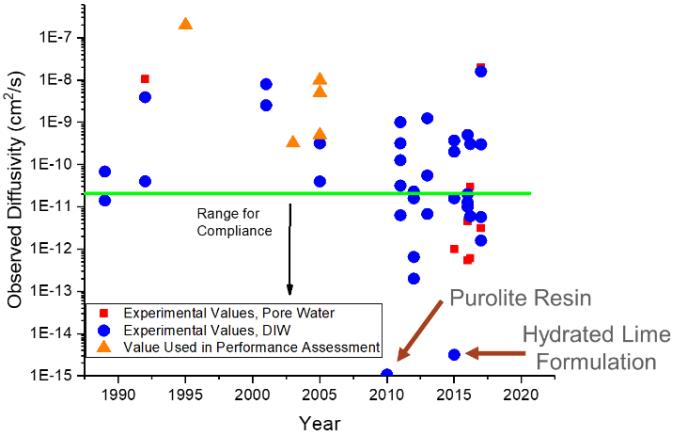
A.3.7 Integrated Disposal Facility Environment Prediction

The NDAA17 report (SRNL-RP-2018-00687) identified a need for "Use of new effective diffusion coefficients to update predictions of performance in an IDF environment." To date, a grouted LAW inventory has not been included in the IDF PA (RPP-RPT-59958), and the only grout waste forms included were the secondary waste (both liquid and solid). The last assessment was the 2012 Tank Closure and Waste Management (TC&WM) EIS (DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington*), which drew heavily from the 2003 risk assessment (RPP-17675, Risk Assessment Supporting the Decision on the Initial Selection of Supplemental ILAW Technologies).

In summary, no efforts have directly carried out a PA for a primary LAW grouted waste form in the IDF. Recent modeling has identified performance targets within the IDF for a grouted waste form based on back calculations. Summaries of the target performance of the major contaminants is provided. The primary uncertainty is in the long-term maintenance of properties of the waste form but changing properties can be assessed in sensitivity cases in PA modeling.

No efforts have directly taken LAW Cast Stone diffusivities and conducted an IDF PA-style calculation; however, a similar study was performed. PNNL-28992 used model simulations to determine a leachability threshold for an inventory of supplemental LAW in the IDF when only the supplemental LAW inventory was considered.

In this study, four radionuclides and contaminants were considered: technetium, iodine, nitrate, and chromium. The work focused on comparing historical Hanford grout leachability data (Figure A-1) against this threshold to identify where improvements may be required. The performance metric defined in the report is intended to allow a rapid assessment to determine if new laboratory data would improve contaminant release from a grouted inventory in the IDF PA.



Source: PNNL-28992, 2019, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Pacific Northwest National Laboratory, Richland, Washington.

Figure A-1. Comparison of Historical Technetium Leach Test Data from Experimental Results (blue dots/red squares) and Those Used in Prior Performance/Risk Assessments (orange triangles). The green line is the performance metric.

The performance metric was defined as a retardation factor (R-value) that is used in reactive transport modeling to define the retention capacity of a waste form relative to a mobile (i.e., non-sorbing/non-reacting) species. The reported R-value represents a minimum needed to maintain contaminant concentrations below the groundwater compliance standard when the grout properties are held constant and only the supplemental LAW inventory is considered. For comparison purposes, R can be converted to a corresponding laboratory-observed diffusivity value (D_{obs}) measured in leach testing or to an overall fractional release rate from the IDF in reactive transport modeling.

The R performance metric was determined through an iterative set of simulations varying the grout waste form distribution coefficient (Kd) and monitoring the resulting transport to groundwater and all other properties. Note that changes in the inventory of each contaminant, or property evolution of the waste forms were not considered in this effort.

An overview of the evaluation for each of the four contaminants is provided below.

Technetium

The R value calculated for technetium correlated to a fractional release rate of 2.1×10^{-6} yr^{-1}, which would be equivalent to a waste form that would measure a D_{obs} of approximately 2×10^{-11} cm^2/s in laboratory leach testing. Assessing historical laboratory data against this value, Figure A-1 shows that previous assumptions for IDF modeling, being conservative to account for unknown reoxidation rates and degradation, were above the metric but several laboratory tests have measured technetium observed diffusivities below the limit. These improved cases include LAW Cast Stone, getter-containing systems, and hydrated-lime-based formulations for secondary waste (assuming that a majority of the waste form retains the conditions leading to the retention).

Note that the "high" orange triangles around 2005 in Figure A-1 represent the recommended values used in the Hanford Tank Closure and Waste Management Environmental Impact Statement (TC&WM EIS, DOE/EIS-0391). These observed diffusivities represent technetium release from an oxidized grout waste form. Even with lower values measured at the time (1×10^{-10} to 2.1×10^{-14} cm^2/s for iodine and from 8×10^{-9} to 4.5×10^{-13} cm^2/s for ^{99}Tc (PNNL-13639, *Diffusion and Leaching of Selected Radionuclides (Iodine-129, Technetium-99, and Uranium) through Category 3 Waste Encasement Cement, Concrete, and Soil Fill Material*), a conservative assumption was made. Observed diffusivities of 5×10^{-9} cm^2/s for ^{99}Tc and 1×10^{-10} cm^2/s for iodine were selected.

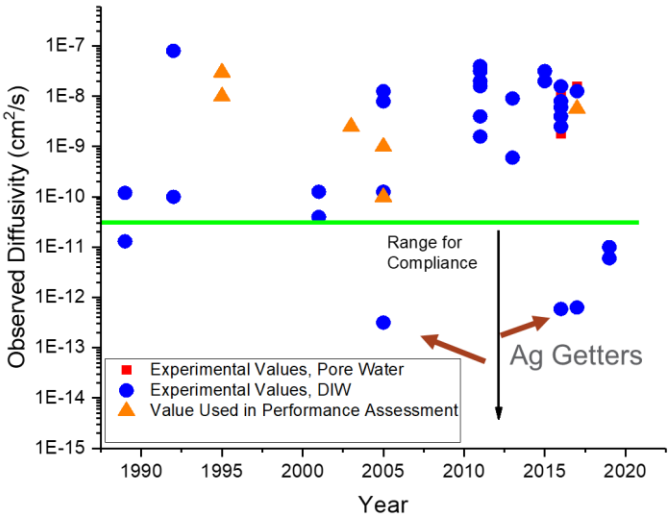
DOE (2005) technical guidance document covers the decision to use an oxidized grout.

> *"The analysis shall consider degradation of grout after a period of 500 years. For purposes of analysis, values to be used for Tc-99 and iodine are listed below. If appropriate, additional sensitivity analysis will be conducted."*

Iodine

The iodine R value corresponds to a fractional release rate of 5.4×10^{-5} yr^{-1}, which is equivalent to an observed diffusivity of approximately 3×10^{-11} cm^2/s in leach testing. Analysis of historical iodine D_{obs} showed that most iodine observed diffusivities range between 1×10^{-8} cm^2/s and 1×10^{-9} cm^2/s, Figure A-2. Achievement of diffusivities that would meet the performance metrics would require either a minimum of ~10× improvement in retention or a similar reduction in inventory.

The one exception to this finding was for formulations containing Ag-based getters with getter loadings >5 wt% in the waste form, described in Section A.3.5.

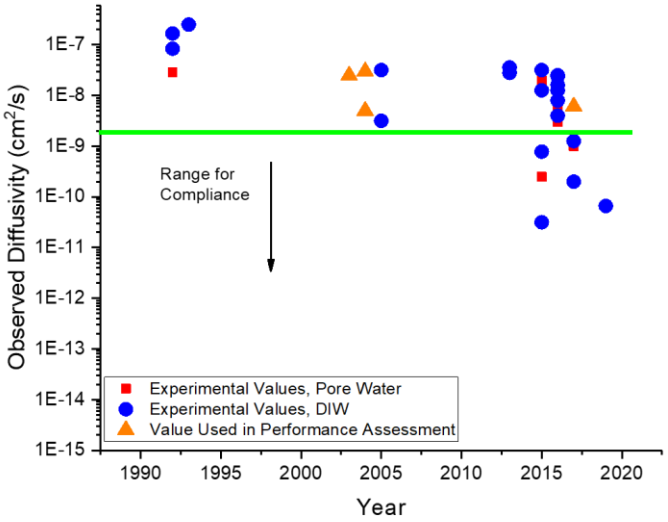


Source: PNNL-28992, 2019, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Pacific Northwest National Laboratory, Richland, Washington.

Figure A-2. Comparison of Historical Iodine Leach Test Data from Experimental Results (blue dots/red squares) and Those Used in Prior Performance/Risk Assessments (orange triangles). The green line is the performance metric.

Nitrate

A fractional release rate of 1.1×10^{-5} yr^{-1}, or a D_{obs} of 2×10^{-9} cm^2/s, would be given for a waste form with the performance metric R value. Of all nitrate leach data assessed, only a small number of tests (from immobilized liquid secondary waste) measured an observed nitrate diffusivity below the limit established by the performance metric (Figure A-3), although the cause of the lowered release values is not known. However, a magnitude 10× decrease from the average nitrate D_{obs} (which corresponds to a 3.2× reduction in release rate) would likely meet the metric. This is contrary to the perception of nitrate having a large impact on groundwater from a grouted supplemental LAW inventory in the IDF. The simulations were also conservative with respect to subsurface behavior of nitrate but should be noted the simulations only consider the contribution from a supplemental LAW inventory (see Volume II, Appendix E, Section E.3.1.5).

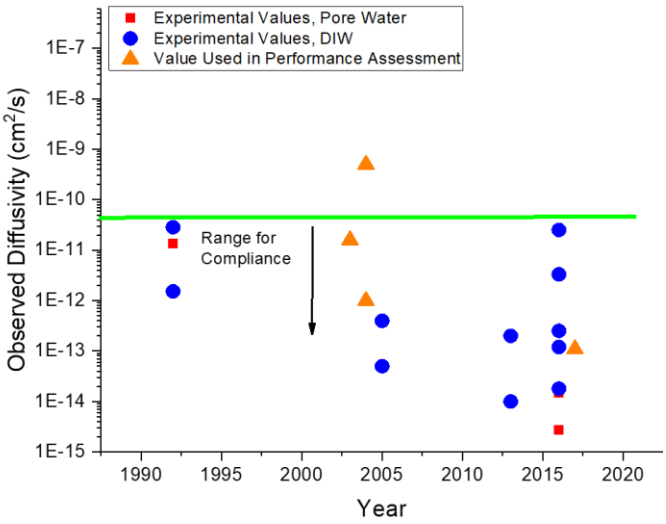


Source: PNNL-28992, 2019, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Pacific Northwest National Laboratory, Richland, Washington.

Figure A-3. Comparison of Historical Nitrate Leach Test Data from Experimental Results (blue dots/red squares) and Those Used in Prior Performance/Risk Assessments (orange triangles). The green line is the performance metric.

Chromium

Very low chromium release rates, relative to other contaminants, have been observed to date in leach tests in BFS-containing systems. A reducing environment is highly favorable for chromium retention (Langton, 1988), and there is evidence in the literature of Cr(VI) anionic species incorporating into the minerals of hardening cement paste (Park et al., 2006). All but one of the reported observed diffusivities for chromium in Figure A-4 fall below the performance metric that corresponds to a fractional release rate of 3×10^{-6} yr^{-1} or D_{obs} of 4×10^{-11} cm^2/s. Maintenance of reduction capacity is likely crucial in chromium retention in the IDF and approaches to predict or improve this are available.



Source: PNNL-28992, 2019, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Pacific Northwest National Laboratory, Richland, Washington.

Figure A-4. Comparison of Historical Chromium Leach Test Data from Experimental Results (blue dots/red squares) and Those Used in Prior Performance/Risk Assessments (orange triangles). The green line is the performance metric.

A.4 RELEVANT INFORMATION

A.4.1 Material Availability

This subsection provides information regarding the availability of the primary dry reagents used in Hanford grout waste from research to date. In summary, material limitations are unlikely but if they arise other dry reagents can be substituted without sacrifice of waste form characteristics (discussed in Section A.2.2).

To sustain operations of a grout process, a large supply of dry reagents is required. While the volume of dry ingredients required for a Hanford supplemental LAW treatment mission may seem large, compared to domestic use of these reagents (e.g., infrastructure) the volume is practical. The availability of reagents was discussed in SRNL-RP-2018-00687, Section C.1.3, with a focus on blast furnace slag and fly ash. The NDAA17 report also summarized that neither BFS nor FA supplies would be a hurdle to a supplemental LAW grout mission. The following summary is derived from data generated by WRPS (TOC-PRES-22-1449, "Fact Sheet – Availability of Grout-Forming Materials for Hanford Waste Treatment").

For BFS, the projected requirement for a supplemental LAW grout mission is ~9,900 tons/year. As of 2019, domestic production of BFS was 8,800,000 tons/year (Table A-3). Projected uncertainties with BFS are closure/idling of blast furnaces, depletion of existing slag piles, regulation of coal-fired plants, increased consumption of BFS as a replacement for FA, and possible limitations on imports.

Table A-3. Domestic Slag Production and Usage Summary

	2013	2014	2015	2016	2017	2018
Total slag production	17.1	18.3	19.5	17.3	17.6	17.6
Imports for consumption	1.9	2.0	1.7	2.2	2.3	2.4
Exports	<0.055	<0.055	<0.055	<0.055	<0.055	<0.055
Blast furnace slag	8.5	9.1	9.8	8.7	8.8	8.8

U.S. Slag Commodity Summary (million short tons)

- BFS taken at 50% of total slag production + imports for consumption.
- One short ton = 2,000 lb
- One metric ton = 2,204.62 lb

With a change in BFS source, changes in the properties of BFS are expected to be minimal with changes in sources, as evidenced by the comparison in PNNL-22747. However, the overall risk of BFS availability is low.

Similar to BFS, a projected requirement for FA in a supplemental LAW grout mission is ~9,900 tons/year, while FA production was at 38,200,000 tons/year. Not all FA is suitable for use in grout waste forms or concrete, and Class F and Class C are the most commonly used types. For FA, the primary uncertainties in the long-term are the declining production of FA with the closure of coal-fired plants and limitations on imports. Locally to Hanford, the availability of FA is changing. Most of the Cast Stone research to date has used FA from the Centralia, Washington, coal-fired power plant, which is slated for closure. Recent work by VSL has studied replacement of this FA with a different source, with little change in waste form properties (VSL-21R5000-1).

A.4.2 Scalability of Grout Waste Forms/Laboratory to Field Considerations

There is extensive work today in the deployment of grout waste forms for the immobilization of liquid and solid wastes (see Volume II, Appendix L). This subsection provides a summary of engineering/pilot demonstrations of grout waste forms at Hanford to date and, where applicable, how the scaled waste form compared to bench-scale samples. There is high confidence in the ability to scale a grout formulation for Hanford LAW.

Grout waste forms have shown consistency in scaling from the laboratory-/bench-scale to demonstration scale. Scaling of these processes is mainly done to study properties related to facility processing or to study proposed alterations to an established flowsheet or system. Relevant to Hanford, there have been several scaled demonstrations of grout waste forms that provide examples.

The original Hanford flowsheet involved large grout disposal vault units to receive grouted DST waste. In development of these vaulted waste forms, four steps were taken: (1) laboratory formulation studies and modeling, (2) laboratory-scale variability studies, (3) pilot-scale verification tests, and (4) real waste testing at laboratory-scale (PNL-SA-21514, *Pilot Scale Verification Test for Hanford Grout*). A pilot-scale facility was constructed in the mid-1980s to support the Hanford Grout Treatment Facility (~4,000 gal capacity) (PNL-6148, *Pilot-scale Grout Production Test with a Simulated Low-Level Waste)*. The pilot-scale study of a proposed formulation for waste from Tank AN-106, prior to the cease of operations of the grout vault, showed that a minor formulation modification was required to slow flow from the pipe discharge of the plant, but other properties were as anticipated (PNL-SA-21514).

Following the pouring of the demonstration phosphate/sulfate waste vault, cores were extracted from the vault. The performance of the cores for compressive strength and leachability exceeded projected limits and were comparable to prior development (Huang et al., 1994).

In the screening test efforts of Cast Stone for supplemental LAW in 2014, a scaled demonstration of LAW Cast Stone was performed (SRNL-STI-2014-00428, *Engineering Scale Demonstration of a Prospective Cast Stone Process*). In this demonstration, a 1,600-gallon tank was filled with Cast Stone from a LAW simulant using the Scaled Continuous Processing Facility at SRNL (SRNL-STI-2014-00406, *Saltstone Studies Using the Scaled Continuous Processing Facility*) that is used to support pilot scale studies of Saltstone. No unexpected behavior was observed in the demonstration, and the properties of the large-scale sample were similar to those from small molded samples prepared at the time of pouring the large block (SRNL-STI-2015-00678, *Analysis of Monolith Core from an Engineering Scale Demonstration of a Prospective Cast Stone Process*). The main difference was a change in chromium leach behavior, which was attributed to inadequate samples storage between test sets that allowed oxidation to occur.

During the down-selection of a baseline formulation for liquid secondary waste at Hanford, engineering-scale demonstrations of two candidate formulations (Ceramicrete and DuraLith) were performed making samples between 55 and 90 gallons in size (PNNL-20751, *Engineering-Scale Demonstration of DuraLith and Ceramicrete Waste Forms*). Both formulations were successfully prepared at scale with minor formulation changes to attain suitable workability. The properties of the large samples were again comparable to laboratory-scale samples.

In 2021, a scaled demonstration using an ammonia-tolerant grout, which is a sulphate-activated slag cement for liquid secondary wastes generated at the Hanford ETF (VSL-21R4950-1, *Maturation of Grout Formulation and Immobilization Technology for Effluent Treatment Facility High-Ammonia Waste*). Samples at 55- and 110-gal scale were prepared, and the results show good consistency from laboratory- to 110-gal-scale. These observations were reported to "*increase the confidence in the full-scale application of this process for stabilization of the ETF waste stream*."

Other cases of grout waste form production at full-scale are described in Volume II, Appendix L, including 17 Mgal of Saltstone produced. The primary item of interest in scaled testing is demonstrating suitable processing parameters, while the physical properties are assumed to be fairly constant with the development scale. No demonstration of getter use at scale has been performed to date. However, with increased scale, the grout waste forms have a reduced surface area to total volume ratio, meaning that less of the waste form inventory is exposed to the environment, and performance can improve as a result.

A.5 REFERENCES

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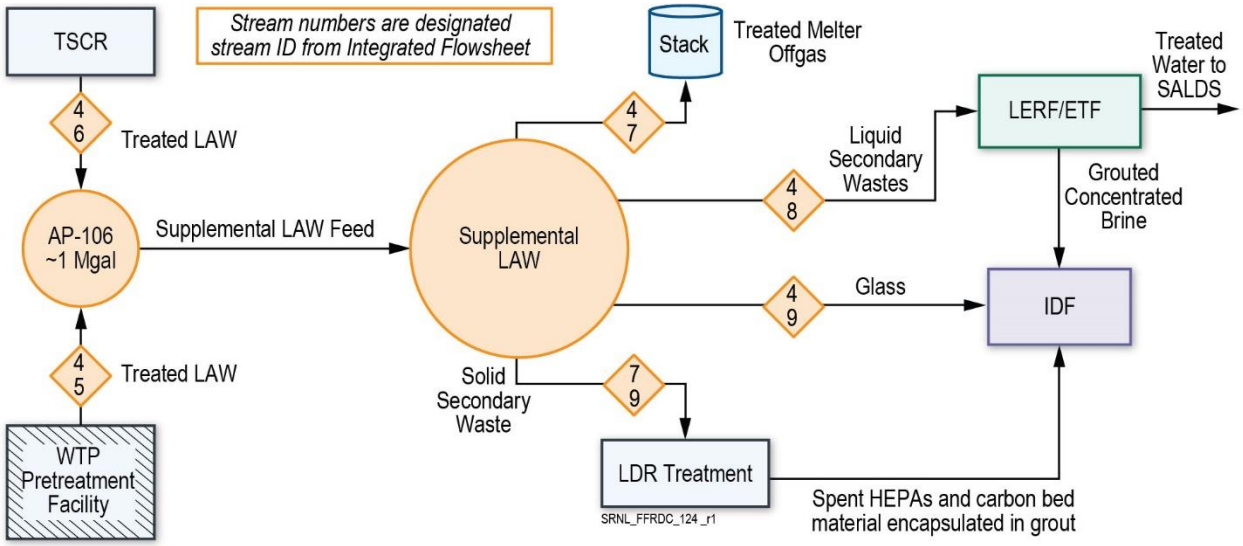
Appendix B. Feed Vector

B.1 INTRODUCTION

The Hanford River Protection Project (RPP) is a combined effort across multiple contractors and facilities to treat and dispose of tank wastes generated during plutonium production at the Hanford Site. The waste is currently stored in large underground storage tanks and must be removed from these tanks, processed (or pretreated) to divide the waste into low-level waste (LLW) (typically described as low-activity waste [LAW]) and high-level waste (HLW) fractions, and then treated/immobilized for disposal.

The Hanford Waste Treatment and Immobilization Plant (WTP) is a complex of facilities (24590-WTP-RPT-PT-02-005, *Flowsheets Bases, Assumptions, and Requirements*) designed to receive waste from the waste storage tanks, perform all pretreatment processes needed to prepare the waste for immobilization, and then immobilize the waste in borosilicate glass (ORP-11242, *River Protection Project System Plan* [System Plan]). A simplified diagram showing the tank farms, WTP, and other required waste treatment facilities is shown in Figure B-1.

The supplemental LAW treatment mission/scope is defined by the One System Integrated Flowsheet as the capacity needed to immobilize the excess treated LAW supernate once the full capacity of the WTP LAW Vitrification Facility is exceeded. The excess supernate is generated because the amount of LAW supernate needed to transfer HLW to the WTP, combined with the supernate generated during HLW pretreatment (washing and leaching operations) along with the supernate needing treatment from the tank farms, is greater than the capacity of the current WTP LAW Vitrification Facility. If WTP processing was adjusted to process all LAW without exceeding the LAW vitrification capacity, HLW processing rates would have to be reduced and the overall RPP mission length would be significantly extended.



Stream	Description
45	Treated LAW feed to supplemental LAW treatment facility from pretreatment
46	Treated LAW feed to supplemental LAW treatment from TSCR *or similar*
47	Stack exhaust from supplemental LAW treatment facility
48	Liquid secondary waste from LAW to Liquid Effluent Retention Facility (LERF)/Effluent Treatment Facility (ETF)
49	Immobilized LAW to Integrated Disposal Facility (IDF)
79	Solid secondary waste to a facility to treat waste to permit disposal

Figure B-1. Simplified Flowsheet for Supplemental Low-Activity Waste Treatment in the Integrated Flowsheet

The supplemental LAW treatment facility is expected to receive feed from Tank AP-106, which could receive feed from two sources: a direct feed process similar to the tank-side cesium removal (TSCR) system, and the WTP Pretreatment (PT) facility. The "SLAW feed vector" (i.e., the composition and amount of supplemental LAW feed as a function of time) is based on the TOPSim model run by Washington River Protection Solutions, LLC (WRPS) of the entire tank immobilization process for the System Plan (ORP-11242, Rev. 9). The System Plan Scenario 1B (ORP-11242, Rev. 9) was used to specify the feed vector for this evaluation, as the most current available System Plan, to allow an assessment of the feasibility of each technology under consideration. However, the WTP PT Facility may not be completed, so the feed vector was adjusted to include the strontium removal expected if all of the feed is processed through systems similar to TSCR.

The technology for supplemental treatment of LAW has not been formally selected; however, vitrification is assumed to be the baseline in the Integrated Flowsheet, with grout considered as an option during the System Plan evaluations. The supplemental LAW treatment facility is assumed to receive LAW from a TSCR or similar direct-feed option, treat the LAW as needed for disposal, package and ship the waste to a disposal facility, and internally handle any secondary wastes. The flow diagram for supplemental LAW treatment is shown in Figure B-1.

This feed vector represents a snap-shot in time, and the actual sequencing of waste is unlikely to be the same as assumed in the current System Plan (ORP-11242, Rev. 9). In addition, this feed vector applies only to the alternatives with a single treatment facility for supplemental LAW treatment that begins operations at the date specified in the System Plan. Use of a modular approach, early or delayed starts, or other changes from the various alternatives being evaluated will impact the feed vector to be treated in terms of both volume and composition. Thus, the feed description is used to guide this evaluation in terms of expected operational ranges for volume and composition, and the evaluation using this feed vector is assumed to be representative enough to allow assessments of the efficacy of each treatment option.

B.2 PROCESSES FOR LOW-ACTIVITY WASTE IMMOBILIZATION AND SUPPLEMENTAL TREATMENT OF LOW-ACTIVITY WASTE

B.2.1 Hanford Tank Waste Background

The Hanford Site generated millions of gallons of radioactive waste during production of nuclear materials. A number of different chemical processes were used at Hanford to separate and purify plutonium, including the bismuth phosphate, reduction and oxidation (REDOX), and plutonium-uranium extraction (PUREX) processes. In addition to the separation processes, cesium and strontium removal and other treatment processes were performed on the tank waste. As a result of the varied processes performed, the wastes stored at Hanford vary significantly in chemical and radionuclide content, although some incidental blending of the various wastes has occurred during storage (LA-UR-96-3860, *Hanford Tank Chemical and Radionuclide Inventories: HDW Model Rev. 4*).

The waste has been stored in 177 underground, carbon steel storage tanks. Several of these tanks are known to have developed leaks and more are suspected to have leaks (PNNL-13605, *A Short History of Hanford Tank Waste Generation, Storage, and Release*); therefore, the pumpable liquid in many of the single-shell tanks (SST) was transferred to double-shell tanks (DST) to eliminate free liquid to the extent possible. The issues with the known leaks and the age of the storage tanks have led to restrictions on the type of processing allowed in the tank farms (RPP-13033, *Tank Farms Documented Safety Analysis*).

B.2.2 Baseline

The Hanford WTP is designed to receive waste from the storage tanks, perform all pretreatment processes to prepare the waste for immobilization, and then immobilize the waste in borosilicate glass (ORP-11242).

The tank waste will be separated into supernate and slurry in the tank farms by allowing solids to settle, then decanting supernate. Slurries will be transferred to WTP Pretreatment or a direct-feed option for HLW (e.g., direct-feed low-activity waste [DFLAW] process). Supernate from the tank farms will be transferred to WTP Pretreatment or TSCR (or similar) in direct-feed options.

HLW processing can generate large volumes of (1) dilute liquid effluents from washing and leaching operations during melter feed preparations, and (2) dilute melter condensate from the vitrification process. These effluents will undergo a similar separation process, as the waste solids will return to the HLW process while the liquid portion is mostly sent to the LAW facilities for treatment. The volume of effluents sent for LAW processing can be greater than the treatment capacity of the WTP LAW Vitrification Facility, with the excess sent to the LAW supplemental treatment facility when combined with the treated feed from the tank farms treatment systems. Approximately one-half of the treated supernate is estimated to be sent to the LAW supplemental treatment facility.

B.2.3 Direct Feed Process

The WTP LAW Vitrification Facility will start operations prior to the WTP PT Facility and HLW vitrification operations. Feed to the LAW Vitrification Facility will require pretreatment for the removal of entrained solids and reduction of the cesium ion concentration. The TSCR system has started operation to treat supernate from the AP Farm, with the treated LAW stored in Tank AP-106. Tank AP-106 had previously stored untreated supernate, but the tank was drained and rinsed as much as practical in preparation for use as a lag storage tank for treated LAW. Melter condensate will be handled by the Effluent Management Facility during direct feeding of LAW from TSCR.

B.2.3.1 Supplemental Low-Activity Waste Feed Vector

The SLAW feed vector calculated for the System Plan Scenario 1B (ORP-11242, Rev. 9) is being used in the evaluation of the feasibility of proposed LAW primary supplemental treatment alternatives. This feed vector represents any remaining LAW supernate generated by pretreatment and TSCR (or similar) processes after the existing WTP LAW Vitrification Facility reaches maximum capacity with no constraints on volumetric flow.

This feed vector represents only one model run of the many alternatives being modeled for the streams assumed to be processed through the supplemental LAW treatment facility. The compositional data from this model run is being used in this analysis, with an adjustment for the ^{90}Sr to account for the expected processing of the streams through TSCR-type systems versus the WTP PT Facility.

The assumptions made during flowsheet model runs (including tank farm retrieval sequencing, assumptions for HLW processing, among others) significantly impact the results. In addition, the values in the feed vector represent deterministic monthly averages versus compositions of each feed campaign. A feed campaign is a large batch (1,000,000 gallons) of feed that will be processed batchwise through the LAW treatment processes. Since each feed campaign is expected to last 3–4 months, a monthly average feed vector provides sufficient detail to capture the variation in the feed.

The actual waste processed through supplemental LAW treatment could be significantly different than the values shown if uncertainties are considered and as the retrieval sequence and HLW processing assumptions evolve.

The varied methods used during nuclear material separations processing at the Hanford Site resulted in waste that varies significantly in composition. Typically, these varying waste types are segregated across the tank farms (although some incidental blending has occurred and will occur during retrieval), which could result in large swings in feed composition to the supplemental LAW treatment facility, as shown in Figure B-2 through Figure B-4. Thus, any supplemental LAW treatment process would have to accommodate the expected extremes in waste feed compositions (when also considering uncertainties), as sufficient lag storage is not expected to be provided to smooth these peaks.

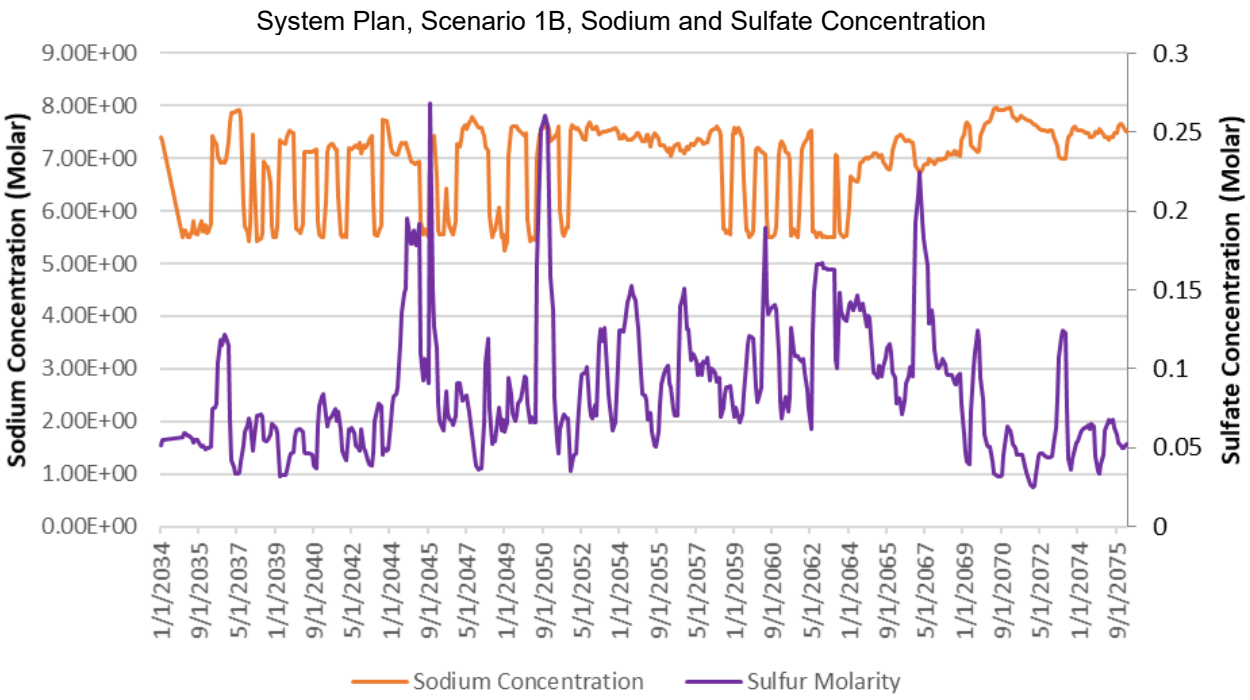


Figure B-2. Sulfur and Sodium Concentrations

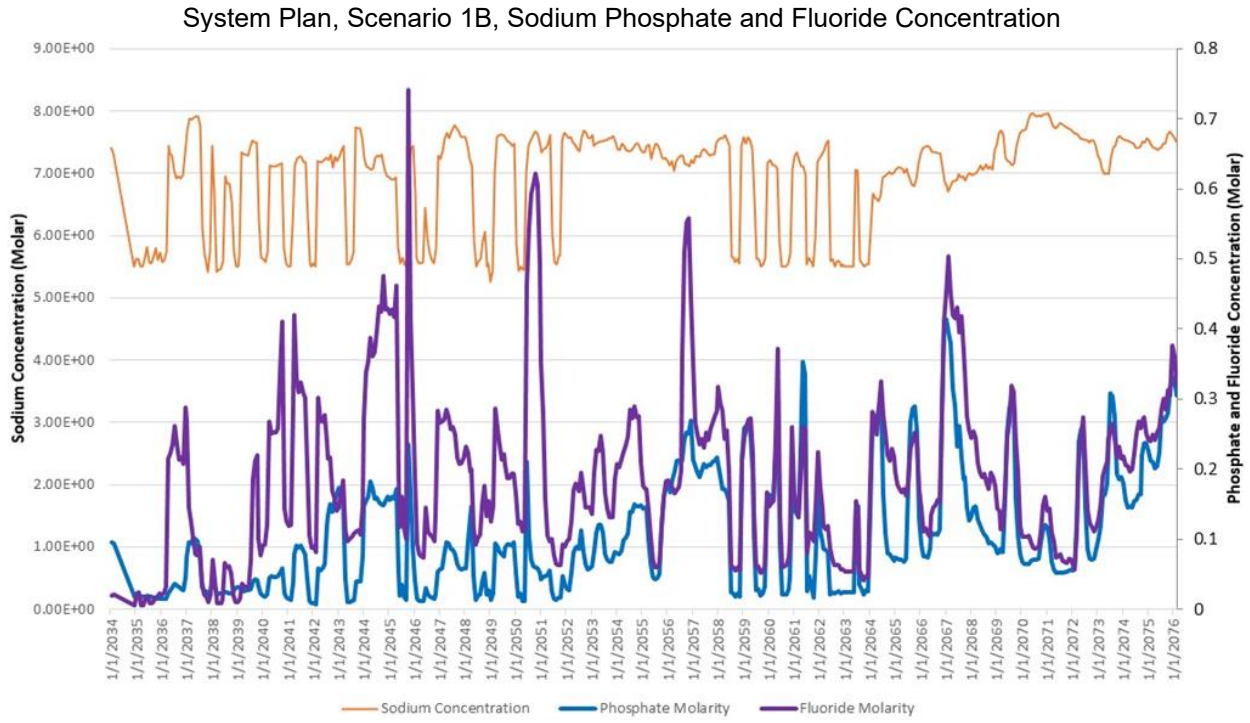


Figure B-3. Phosphate and Fluoride Concentration

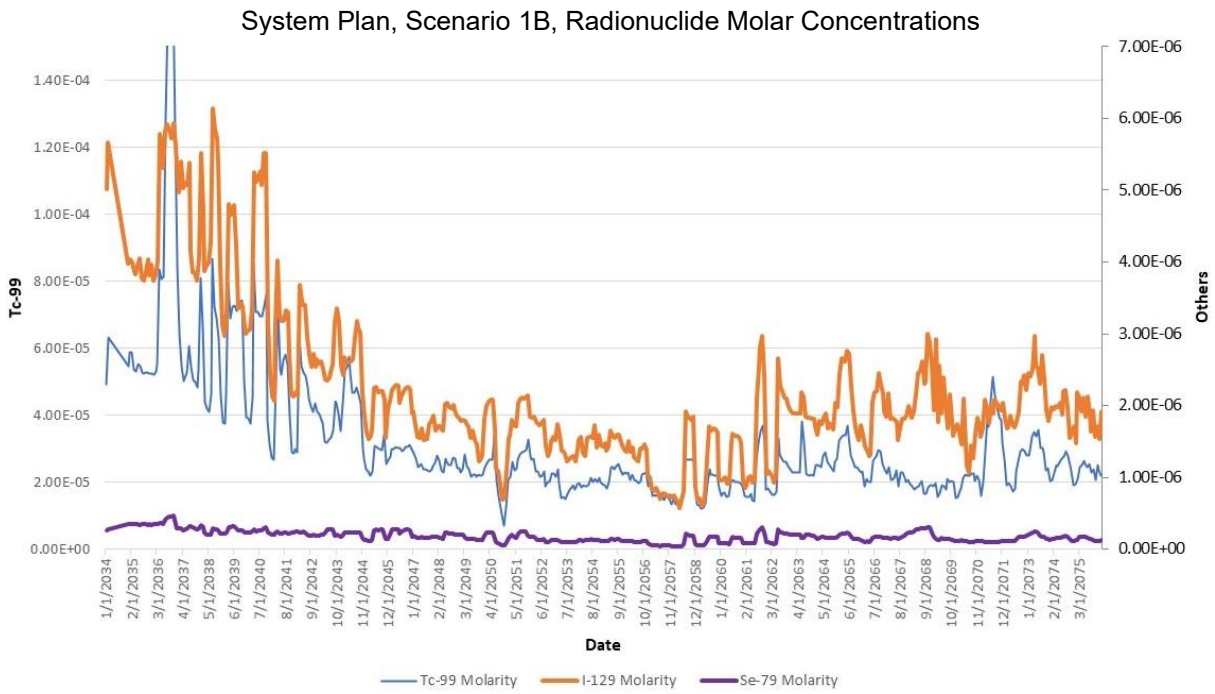


Figure B-4. Key Radionuclide Concentrations

In addition, the initial direct-feed flowsheet for TSCR lacks the evaporator used in the PT Facility to bring the feed up to ~8 M sodium concentration. Until an evaporator is installed after the TSCR processes, the treated supernate will be limited to approximately 5.6 M sodium.

As a result of the unconstrained model and the desire to achieve full capacity through the HLW Vitrification Facility, supplemental LAW treatment would also need to accommodate extremes in feed volume, as shown in Figure B-5.

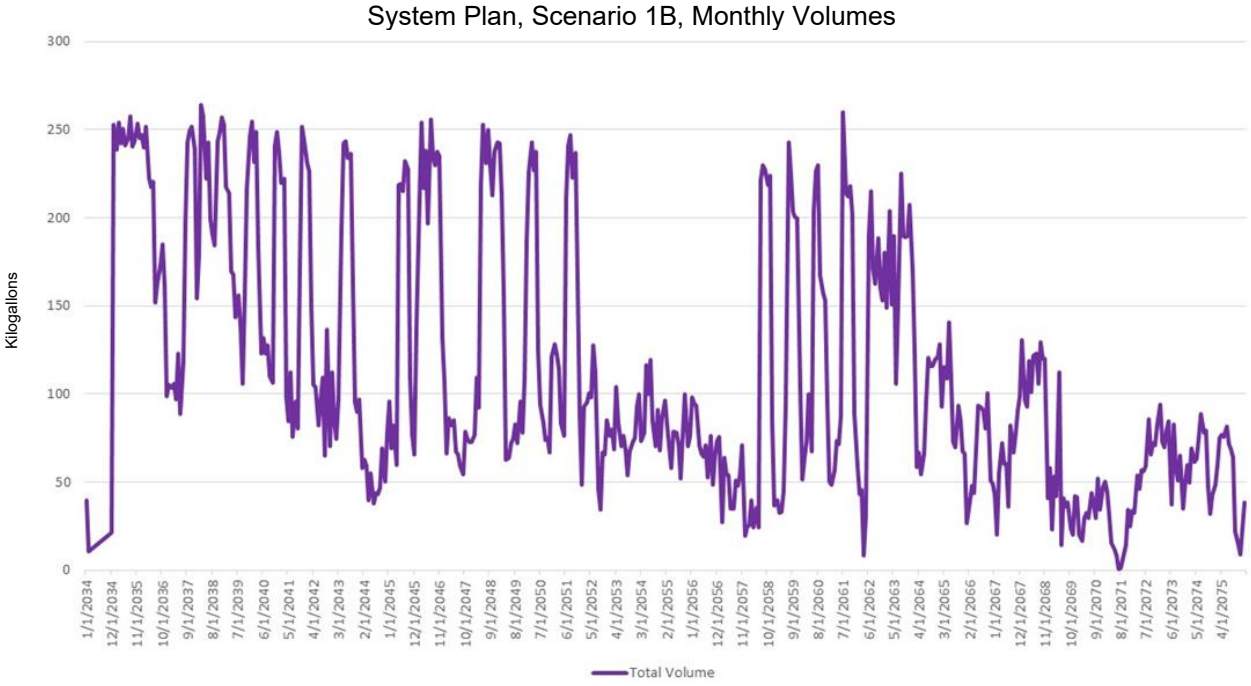


Figure B-5. Supplemental Low-Activity Waste Feed Volumes (kilogallons per month)

The use of the feed vector to determine the required size of the immobilization facility for cost estimation provides a consistent capacity target for each immobilization technology. The cost estimate comparisons are expected to be scalable such that the differences noted in costs would be expected to be similar if a different capacity is chosen for supplemental LAW treatment. 1 Mgal of lag storage is available in Tank AP-106; however, that amount is not sufficient to significantly reduce the required rate from the maximum rates described below.

Feed Vector Details

Monthly Feed Rate

The amount of feed to supplemental LAW treatment each month is highly variable, with an average monthly volume of 114,000 gallons. The maximum volume in one month was more than double the average volume at 264,000 gallons, while the minimum was only 700 gallons. Converted to gallons per minute, the feed rates were 0.02 to 6.1 gal/min, with an average of 2.6 gal/min. As shown above in Figure B-5, the additional feed when direct feed processing (supplemental LAW is fed directly from the tank farms versus WTP) occurs results in the highest feed rates. The feed vectors from System Plan Scenario 1A (ORP-11242, Rev. 9) and other alternative scenarios were also reviewed. Based on the composite information from the deterministic runs reviewed, the maximum feed rate to supplemental LAW treatment was determined to be 360,000 gal/month to allow conservative sizing of the supplemental LAW treatment facility versus the 264,000 gal/month maximum in the baseline (System Plan Scenario 1B).

The main driver for the differences in the monthly rates is the type of tank waste being retrieved and fed through the treatment systems. Some tanks/farms are predominantly sludge solids with little saltcake such that the supernatant liquid volume when retrieving and processing that waste is relatively small compared to retrieving/processing from tanks/farms that have more saltcake than sludge. With the retrieval processing rate dictated by the feed requirements for the HLW Vitrification Facility, the supplemental LAW feed volume is allowed to vary unconstrained in the System Plan.

Chemical Composition

The feed to the supplemental LAW facility in System Plan Scenario 1B (ORP-11242, Rev. 9) from the WTP PT Facility will be an approximate 8 M sodium solution with nitrate the dominant anion. The feed sent to supplemental LAW treatment from direct-feed options will typically be more dilute, with a sodium concentration of approximately 5.6 M, although a waste feed evaporator is added later in the mission to concentrate the feed to the same sodium concentration as feed from WTP. Anions in the feed vector include hydroxide, aluminate, nitrite, carbonate, phosphate, sulfate, fluorine, oxalate, chromate, and chlorine. These species, along with potassium, organic carbon, and silicon, and comprise nearly 100% of the non-water species in the feed. The combined feed composition is shown in Table B-1. Minor species are listed in the table for species with non-zero values in the feed vector data.

Table B-1. Feed Vector Chemical Composition

Analyte	Average	Maximum	Minimum	Units
Sodium	1.6E+02	1.8E+02	1.2E+02	g/L
Nitrate	1.1E+02	2.0E+02	2.9E+01	g/L
Free Hydroxide	4.9E+01	8.8E+01	7.6E+00	g/L
Nitrite	2.8E+01	6.4E+01	6.3E+00	g/L
Carbonate	1.7E+01	4.5E+01	3.2E+00	g/L
Aluminum	1.1E+01	2.6E+01	1.3E+00	g/L
TOC	5.3E+00	7.8E+01	4.9E-01	g/L
Fluorine	3.6E+00	1.4E+01	1.0E-01	g/L
Phosphate	3.3E+00	1.3E+01	2.4E-01	g/L
Oxalate	3.1E+00	1.4E+01	3.4E-01	g/L

Table B-1. Feed Vector Chemical Composition

Analyte	Average	Maximum	Minimum	Units
Sulfur	2.8E+00	8.6E+00	8.1E-01	g/L
Chlorine	1.7E+00	4.2E+00	4.6E-01	g/L
Potassium	1.2E+00	6.5E+00	1.7E-01	g/L
Silicon	6.6E-01	3.7E+00	4.7E-02	g/L
Cerium	8.1E-02	2.5E-01	1.6E-05	g/L
Calcium	7.6E-02	4.2E-01	1.2E-02	g/L
Ammonia	6.3E-02	2.0E-01	0.0E+00	g/L
Iron	6.1E-02	4.3E-01	1.9E-03	g/L
Manganate	5.9E-02	2.0E+00	0.0E+00	g/L
Peroxide	2.9E-02	9.1E-02	0.0E+00	g/L
Bound Hydroxide	2.7E-02	9.0E-01	5.1E-05	g/L
Nickel	2.3E-02	2.2E-01	1.8E-03	g/L
Zirconium	1.8E-02	3.0E-01	5.5E-04	g/L
Lead	1.2E-02	9.1E-02	3.7E-04	g/L
Bismuth	9.9E-03	4.9E-02	6.7E-04	g/L
Selenium	7.3E-03	2.5E-02	1.2E-04	g/L
Manganese	3.5E-03	5.2E-02	1.2E-04	g/L
Molybdenum	2.7E-03	2.1E-02	3.9E-07	g/L
Mercury	2.6E-03	9.7E-03	1.6E-04	g/L
Boron	2.3E-03	1.7E-02	1.4E-05	g/L
Strontium	1.9E-03	2.2E-02	3.4E-04	g/L
Cadmium	1.8E-03	2.9E-02	3.9E-05	g/L
Thallium	1.4E-03	3.2E-02	1.3E-07	g/L
Antimony	1.3E-03	7.7E-03	1.7E-05	g/L
Tungsten	1.2E-03	2.9E-02	1.4E-07	g/L
Arsenic	9.3E-04	8.4E-03	1.7E-07	g/L
Neodymium	7.9E-04	7.8E-03	1.2E-07	g/L
Zinc	6.2E-04	7.8E-03	1.2E-07	g/L
Magnesium	5.2E-04	7.2E-03	1.2E-07	g/L
Copper	4.6E-04	1.2E-02	5.5E-08	g/L
Cobalt	2.9E-04	2.2E-03	8.6E-06	g/L
Sliver	2.8E-04	3.4E-03	1.2E-07	g/L
CrOOH	2.6E-04	1.6E-02	0.0E+00	g/L
Vanadium	2.5E-04	3.6E-03	4.5E-08	g/L
Barium	2.4E-04	2.7E-03	5.1E-08	g/L
Lithium	2.0E-04	3.0E-03	4.5E-07	g/L
Lanthanum	1.9E-04	1.7E-03	5.0E-06	g/L
Titanium	1.1E-04	7.9E-04	1.5E-08	g/L
Yttrium	1.0E-04	2.7E-03	1.1E-08	g/L
Ruthenium	8.5E-05	2.0E-03	6.5E-08	g/L
Rubidium	6.7E-05	1.7E-03	4.9E-09	g/L
Hydroxide (s)	6.6E-05	0.0E+00	0.0E+00	g/L
Praseodymium	5.7E-05	1.5E-03	1.8E-09	g/L
Tantalum	5.6E-05	1.4E-03	4.1E-09	g/L
Beryllium	5.3E-05	4.2E-04	1.9E-08	g/L
Tellurium	5.0E-05	1.2E-03	2.6E-09	g/L
Praseodymium	4.9E-05	1.3E-03	2.2E-09	g/L

Table B-1. Feed Vector Chemical Composition

Analyte	Average	Maximum	Minimum	Units
Cyanide	4.5E-05	1.0E-03	5.3E-09	g/L
Rhodium	3.6E-05	8.6E-04	4.0E-09	g/L
Thorium	9.3E-07	1.8E-05	2.2E-08	g/L
Cesium	6.9E-07	5.3E-06	7.6E-08	g/L

Notes:
- Insoluble sodium is included in the average value, but not in the maximum and minimum values due to the low concentration compared to soluble sodium.
- These species are mostly insoluble as shown in the feed vector data. The values shown sum the insoluble and soluble contributions.
- The averages shown are simple averages of the monthly compositions. The averages are not weighted by the total volume processed each month.

TOC = total organic carbon.

Many of the anions and organics in the feed will react to form gaseous products during high temperature processes (e.g., vitrification or steam reforming), while a low temperature process like grout will incorporate these species into the grouted waste form along with the water in the feed. Nitrate, nitrite, carbonate, and formate will react to form nitrogen, nitrogen oxides (NO_x), ammonia, CO_2, and CO in the vitrification and steam reforming processes. The amount of each gas generated will depend on many factors during processing, including the amount of reducing agents added, temperature, and residence time in the high temperature process.

Speciation of the total organic carbon (TOC) is not part of the Hanford Best Basis Inventory (BBI) (in addition, the TOPSim model does not use all of the limited available speciation data), with the exception of a small number of analytes (e.g., acetate, formate, and oxalate). Because of uncertainties, subtracting the acetate, formate, and oxalate species tabulated in the BBI from TOC often results in a very small or negative value for total TOC, as shown in Figure B-6.

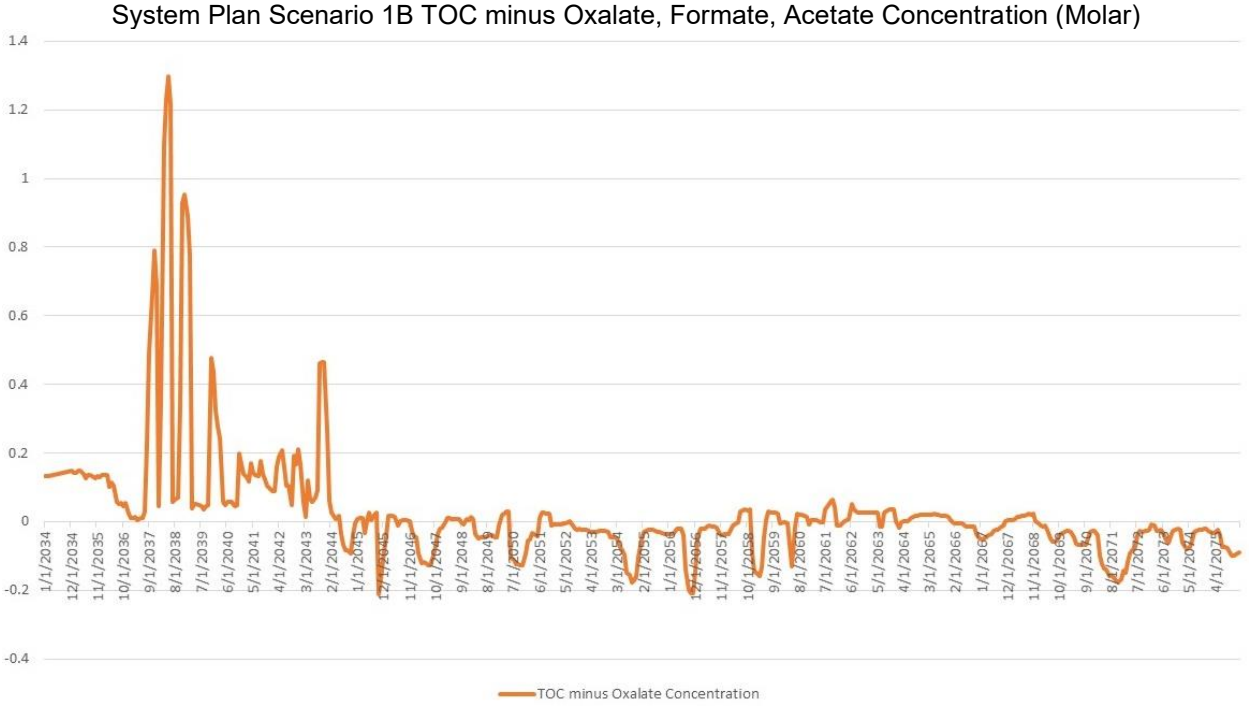


Figure B-6. Total Organic Carbon

Significant amounts of TOC remain after subtraction when processing wastes from tanks known to have organic complexants. A detailed evaluation of organics in the tank wastes and potential for removal by evaporation has been recently performed; the organics from that evaluation have been used in this analysis (SRNL-STI-2020-00582, *Hanford Supplemental Low Activity Waste Simulant Evaporation Testing for Removal of Organic*).

Complexant Wastes

Strontium was recovered from tank waste using processes that included the addition of complexants (EDTA [ethylenediamine-tetraacetic acid], HEDTA [hydroxyethylethylenediaminetriacetic acid], and glycolate) to the waste (CNWRA 97-001, *Hanford Tank Waste Remediation System Familiarization Report*). Significant amounts of these complexants remained in the tank waste after the process was completed. Thus, a portion of the tank waste at Hanford contains concentrations of organic species at much higher concentrations than the remaining wastes. This waste is often designated as "complexant" waste. Tanks AN-102 and AN-107 are the two tanks that contain the majority of this waste.

Solids in the LAW Feed/Recycle Streams

Solid species in the feed vector form during evaporation of the combined treated LAW and WTP LAW vitrification recycle stream in the WTP PT Facility and would also form if an evaporator is added to direct-feed options. Additionally, some carryover of glass-forming chemicals in the WTP LAW vitrification recycle is expected. This carryover is not included in the TOPSim model and is not shown in the SLAW feed vector presented here. Given the small amount of expected carryover, this omission would not likely significantly impact the evaluation of the supplemental treatment technologies for LAW.

Radionuclides in Feed Vector

The radionuclides in the feed vector are shown in Table B-2 and Figure B-7. ^{90}Sr and ^{151}Sm are the two dominant radionuclides shown in the feed vector. These two species account for 94% of the total activity; 99% of the activity in the supplemental LAW feed is accounted for when ^{99}Tc, ^{63}Ni, and ^{137}Cs are added.

The crystalline silicotitanate (CST) sorbent media used for TSCR during DFLAW processing has a strong affinity for strontium and some affinity for americium, neptunium, and plutonium. Therefore, the SLAW feed vector may have much less of these radionuclides if CST is used to remove cesium from the feed as is planned during DFLAW processing. The WTP PT Facility would use a resorcinol-formaldehyde resin for cesium removal, which would not be expected to remove the americium, neptunium, plutonium, or strontium. CST is assumed in this review to be used for cesium removal for the full WTP mission. The adjusted amounts column accounts for strontium removal by CST.

Table B-2. Radionuclides in Feed Vector

Radionuclide	Total Amount in Feed (Ci)	Adjusted Amount (Ci)	Radionuclide	Total Amount in Feed (Ci)	Adjusted Amount (Ci)
^{90}Sr	3.0E+05	3.0E+03	^{238}U	5.3E+00	5.3E+00
^{151}Sm	5.1E+04	5.1E+01	^{242}Cm	4.6E+00	4.6E+00
^{99}Tc	1.2E+04	1.2E+04	^{237}Np	4.4E+00	4.4E+00
^{63}Ni	5.9E+03	5.9E+01	^{244}Cm	3.3E+00	3.3E+00
^{137}Cs	1.5E+03	1.5E+03	^{60}Co	2.2E+00	2.2E+00
^{241}Am	1.3E+03	1.3E+03	^{152}Eu	2.1E+00	2.1E+00
^{93}Zr	4.6E+02	4.6E+02	^{155}Eu	2.0E+00	2.0E+00
^{93m}Nb	4.6E+02	4.6E+02	^{243}Am	6.3E-01	6.3E-01
^{14}C	3.5E+02	3.5E+02	^{231}Pa	4.8E-01	4.8E-01
^{239}Pu	3.3E+02	3.3E+02	^{227}Ac	3.2E-01	3.2E-01

Table B-2. Radionuclides in Feed Vector

Radionuclide	Total Amount in Feed (Ci)	Adjusted Amount (Ci)	Radionuclide	Total Amount in Feed (Ci)	Adjusted Amount (Ci)
^{79}Se	2.2E+02	2.2E+02	^{125}Sb	2.4E-01	2.4E-01
^{59}Ni	1.1E+02	1.1E+02	^{243}Cm	2.4E-01	2.4E-02
^{126}Sn	9.5E+01	9.5E+01	^{235}U	2.2E-01	2.2E-01
^{113m}Cd	8.9E+01	8.9E+01	^{236}U	1.4E-01	1.4E-01
^{241}Pu	8.8E+01	8.8E+01	^{232}U	1.3E-01	1.3E-01
^{240}Pu	6.8E+01	6.8E+01	^{228}Ra	4.7E-02	4.7E-02
^{3}H	4.8E+01	4.8E+01	^{232}Th	3.9E-02	3.9E-02
^{154}Eu	2.6E+01	2.6E+01	^{242}Pu	3.1E-02	3.1E-02
^{233}U	1.5E+01	1.5E+01	^{229}Th	2.7E-02	2.7E-02
^{129}I	1.2E+01	1.2E+01	^{226}Ra	1.5E-03	1.5E-03
^{238}Pu	1.2E+01	1.2E+01	^{134}Cs	1.6E-06	1.6E-06
^{234}U	5.3E+00	5.3E+00	^{106}Ru	5.6E-09	5.6E-09

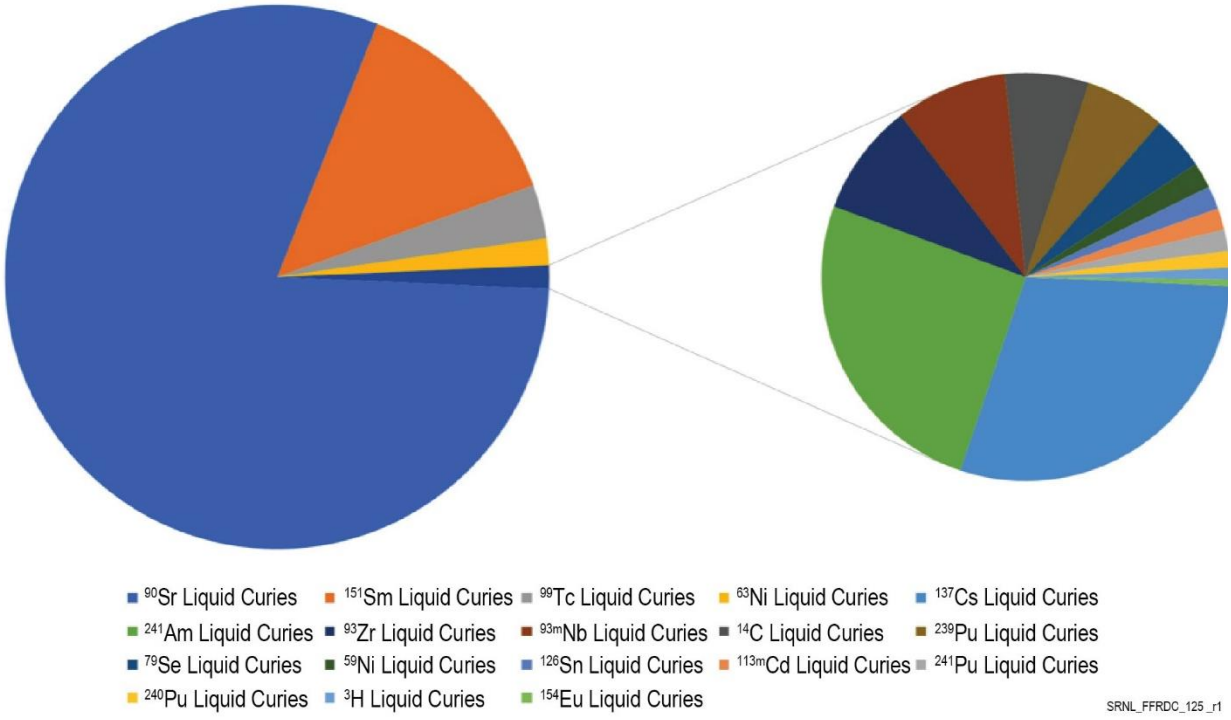


Figure B-7. Radionuclides in Feed Vector Greater than 0.01% of Total Activity

The ^{151}Sm in Hanford tank waste was assumed to be 50% soluble during development of the BBI. Savannah River Site (SRS) experience would indicate that samarium is highly insoluble and may not be present in the feed to supplemental LAW treatment at the levels shown (SRNL-STI-2018-00499, *Results for the Second Quarter Calendar Year 2018 Tank 50 Salt Solution Sample*).

Comparison of SLAW Feed Vector to SRS Saltstone Feed

During the National Defense Authorization Act for Fiscal Year 2017 (NDAA17) analysis (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*), a comparison between SRS Saltstone feed and the Hanford supplemental LAW feed was made. This comparison is copied below without updates to the System Plan Scenario 1B compositions.

The SRS Saltstone facility immobilizes treated supernatant wastes from the SRS tank farm. The SRS tank farm stores wastes generated from the SRS PUREX processes and is the closest analog to the Hanford tank waste. Some differences exist since Hanford used processes other than the PUREX process, and one of the processing facilities at SRS processed a modified PUREX process. In addition, the process to treat the supernatant wastes at SRS uses a monosodium titanate (MST) strike to remove soluble actinides and strontium prior to the filtration step and uses solvent extraction to remove cesium versus an ion exchange process.

A comparison of the supplemental LAW and Saltstone feed for selected parameters is shown in Table B-3. As shown, the major species (sodium and nitrate) are the same as the supplemental LAW feed, and the concentrations of these species are similar. Hydroxide, nitrite, carbonate, and sulfate are also similar in concentration. Aluminate concentrations are ~3× higher in the supplemental LAW feed. Phosphate, fluorine, chlorine, and organic content are 1 to 2 orders of magnitude higher in the supplemental LAW feed since these chemicals are primarily added by the separation processes other than the PUREX process. Mercury is much higher in the Saltstone feed since the modified PUREX process was the primary source of mercury in the SRS tank waste.

The amounts of ^{137}Cs, ^{99}Tc, and ^{129}I are similar in the supplemental LAW and Saltstone feeds. ^{90}Sr is much lower in the Saltstone feed since the SRS tank waste does not have the chelation agents that were added at Hanford, and the MST strike will remove ^{90}Sr if elevated levels are in the feed to the supernatant treatment systems. As noted above, samarium was arbitrarily assigned a solubility value in the BBI. Nickel isotopes are also less than detectable in the Saltstone feed. The chelation agents in the Hanford tank(s) could potentially elevate the solubility of the samarium and nickel in the Hanford waste.

Table B-3. Supplemental LAW Feed Comparison to Savannah River Site Saltstone Feed

Parameter	Supplemental LAW	Saltstone	Units
Sodium	1.80E+05	1.32E+05	mg/L
Nitrate	1.09E+05	1.19E+05	mg/L
Hydroxide	5.83E+04	3.38E+04	mg/L
Aluminate	4.66E+04	1.71E+04	mg/L
Nitrite	2.97E+04	2.60E+04	mg/L
Carbonate	1.89E+04	1.63E+04	mg/L
Phosphate	1.13E+04	3.74E+02	mg/L
Sulfate	9.27E+03	4.49E+03	mg/L
Fluorine	3.96E+03	<1.0E+02	mg/L
Oxalate	3.44E+03	5.04E+02	mg/L
Chromate	2.82E+03	1.14E+023	mg/L
Chlorine	1.73E+03	5.04E+02	mg/L
Potassium	1.41E+03	4.59E+02	mg/L
Total Organic Carbon	1.16E+03	2.1E+02	mg/L
Silicon	7.40E+02	1.86E+01	mg/L
Mercury	3.0E+02	6.7E+011	mg/L
^{90}Sr	1.5E+00	5.71E-02	mCi/L

Table B-3. Supplemental LAW Feed Comparison to Savannah River Site Saltstone Feed

Parameter	Supplemental LAW	Saltstone	Units
^{151}Sm	2.3E-01	<4.11E-05	mCi/L
^{99}Tc	5.4E-02	4.61E-02	mCi/L
^{63}Ni	3.5E-02	<7.52E-08	mCi/L
^{137}Cs	1.0E-02	7.91E-01	mCi/L
^{129}I	5.4E-05	3.33E-05	mCi/L

Notes
- Mercury concentrations have been increasing in the Saltstone feed due to methylated mercury species in the recycle to the SRS tank farm from HLW immobilization processes.
- Saltstone values are from SRNL-STI-2018-00499, *Results for the Second Quarter Calendar Year 2018 Tank 50 Salt Solution Sample.*
- Chromate is calculated from chromium measurement.

HLW = high-level waste. SRS = Savannah River Site.
LAW = low-activity waste.

B.2.3.2 Integrated Flowsheet

The model runs that generated the SLAW feed vector were performed using a TOPSim model, as described in the model requirements document (RPP-RPT-59470, "TOPSim V3.0 Model Requirements") that lists the calculational techniques and assumptions made in the calculations for each unit operation.

The TOPSim model has a number of simplifications that allow the entire Hanford waste disposition flowsheet to be modeled in a timely manner. These simplifications include:

- Single parameter "split factors" to determine partitioning of most species through each unit operation, including the melter and melter offgas system
- Lack of inclusion of the impact of a melter idling on emissions from the melter
- Supplemental LAW treatment modeled as a "black box"
- Flushes of transfer lines in the WTP are not modeled.

The use of single parameter split factors and the lack of impacts from melter idling impact the recycle streams from the HLW and LAW melter offgas systems and could lead to non-conservative assumptions of semi-volatile species (e.g., ^{129}I, ^{99}Tc, sulfur, chlorine, and fluorine) in the feed to supplemental LAW treatment (24590-WTP-MRR-PENG-16-004, *DFLAW Sensitivity Studies for Melter Idling Impacts*). The single parameter split factors do not account for any process variation from changing feed compositions and determining if the impact of this simplification would be conservative or non-conservative is not possible. The lack of flush water additions in WTP in the model primarily reduces the estimated amounts of secondary waste generated from LAW and supplemental LAW processing.

Note that the retrieval sequence and processing assumptions (e.g., direct feed option timing and processing amount) impact the amount of feed processed through supplemental LAW and the composition. As with the split factor assumptions and not considering uncertainties, stating whether the current estimates are conservative or non-conservative is not possible. An assumption in this evaluation is that use of this feed vector would be representative enough to allow assessments of the efficacy of each treatment option.

An additional consideration for using the feed vector is that an integrated flowsheet could potentially be generated that performs acceptably, with some constraints placed on supplemental LAW feeds to prevent the most extreme conditions noted in the current feed vector. Thus, a proposed flowsheet should not be automatically eliminated from consideration if a small set of conditions noted in the current vector are outside the ranges possible with the flowsheet.

One item noted in the review was that some of the monthly averages supplied by WRPS contain sufficient radionuclides that the Class C waste limits are exceeded. These outliers are known to the WRPS team and are assumed to be corrected by either a different blending or processing strategy for those wastes. However, the model run is not repeated to correct these issues unless a significant fraction of the waste feed exceeds limits. Thus, although these outliers exist in the feed vector supplied by WRPS, no waste feeds that would exceed Class C limits are expected during supplemental LAW processing.

Finally, the ^{151}Sm concentrations in the feed vector are notably much higher than comparable streams at SRS. The ^{151}Sm concentration of feed to Saltstone is typically less than detectable, indicating that ^{151}Sm is likely very insoluble in SRS wastes. Thus, the ^{151}Sm concentrations in the SLAW feed vector should be considered bounding.

B.3 FLYWHEELS AND IMPACT ON SUPPLEMENTAL LOW-ACTIVITY WASTE TREATMENT

B.3.1 Flywheel Description

The single pass retention of selected species (e.g., technetium) is less than 50% during the LAW vitrification process due to the high temperature of the melter leading to a portion of these species vaporizing from the melter (24590-WTP-RPT-PT-02-005). The majority of these species are efficiently captured in the condensate from melter offgas such that losses to the stack are minimal.

Exceptions to the efficient capture are mercury and iodine, which are likely to be captured at significantly lower percentages in the primary offgas system (Cree and Wagnon, 2022). Mercury is expected to be captured in the carbon bed that is part of the secondary offgas system, while iodine is likely to be captured in the caustic scrubber (although uncertainty is high for iodine capture). Recycle of the caustic scrubber solution is under consideration for the WTP LAW Vitrification Facility.

To increase the overall retention of technetium, the melter offgas condensate is evaporated to remove water, then recycled to the melter feed. The recycle loop increases the technetium retention, but also recycles species such as chlorine, fluorine, and sulfur, which can decrease the allowable waste loading the glass. Recycling material in this manner increases the concentrations of the species recycling in the recycle "flywheel" until the single pass retention is high enough to purge the species from the flywheel at the same rate as the incoming feed adds the species to the flywheel. This process is shown Figure B-8 for a species with a 33% single pass retention in a simplified flywheel with no losses to the offgas systems.

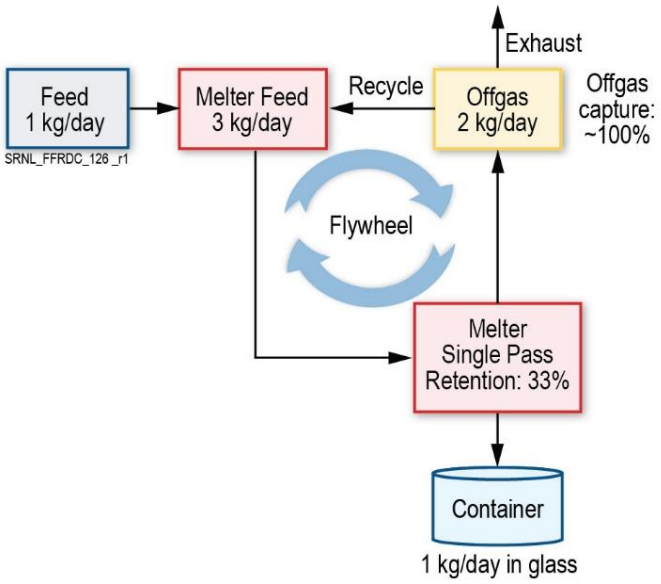


Figure B-8. Simplified Flywheel

Note that the melter feed amount of the species has increased from 1 kg/day in the feed to 3 kg/day in the flywheel to allow a 33% retention to remove 1 kg/day in the glass. If the single pass retention was lower, the concentration in the flywheel would increase. Thus, if single pass retention was 10%, the amount in the recycle would increase to 9 kg/day and the amount in the melter feed would increase to 10 kg/day.

The flywheel in the LAW system after startup of supplemental LAW treatment is more complicated, as is shown in Figure B-9. Note that chlorine, chromium, fluorine, mercury, iodine, sulfur, and technetium are the primary species that will flywheel in the system. Water is also part of the flywheel, requiring the evaporation step in the Effluent Management Facility to purge water. Because the supplemental LAW feed represents an additional purge point, the overall concentration in the flywheel is decreased. In this example, approximately 50% of the melter feed is sent to supplemental LAW treatment; this ratio would change during operation and impact the distributions in the flywheel.

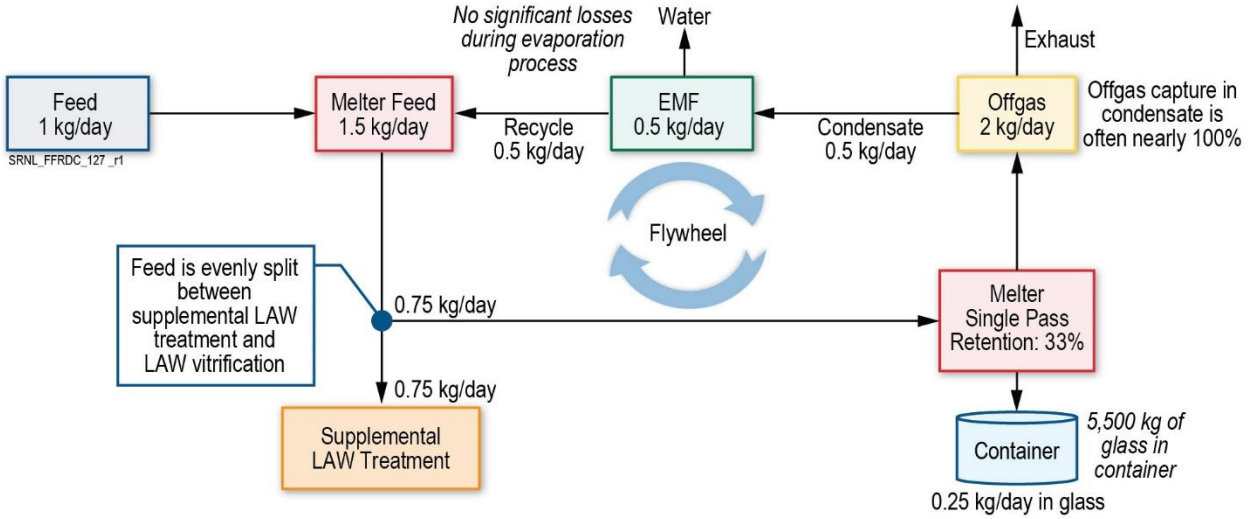


Figure B-9. Low-Activity Waste Flywheel

B.3.2 Impact on Supplemental Low-Activity Waste Treatment

The recycle flywheel could have two significant impacts on supplemental LAW treatment. First, the amount of LAW glass required to immobilize the treated LAW supernate could increase if waste loading is decreased from the higher amounts of chlorine, fluorine, and sulfur, if the single pass retention of these species is lower than assumed in the model. Since the LAW Vitrification Facility is at capacity throughout the WTP mission, an increase in capacity for LAW treatment must occur at the supplemental LAW treatment facility. Therefore, the flywheel could impact the amount of material sent to supplemental LAW treatment.

Second, the composition of the feed to supplemental LAW treatment is impacted if the single pass retention in the LAW flywheel changes. As shown in Figure B-9, 75% of the semivolatile species is sent to supplemental LAW treatment even though the feed volume is evenly split in the example. If the single pass retention of a species is lower, a greater percentage of the species is immobilized at the supplemental LAW facility versus the LAW Vitrification Facility. If the single pass retention is 10% for LAW, approximately 91% of the species will eventually be sent to supplemental LAW treatment even if the melter feed stream flow continues to be split evenly between LAW and supplemental LAW.

Melter idling leads to decreased single pass retention of species since the vaporization of these species from the melt increases during idling, depleting the melt pool and increasing the amounts sent to the offgas system. Melter idling is not modeled during the Integrated Flowsheet; therefore, the overall single pass retention of technetium can be assumed to be less than that assumed in the model.

For comparison to the figures above, the single pass retention of technetium is assumed to be 38% in the Integrate Flowsheet models based on an average of pilot plant retention data (24590-WTP-RPT-PT-02-005).

In addition, if vitrification is chosen as the waste form for supplemental LAW, a similar recycle loop will be required in the supplemental LAW treatment facility to ensure that the technetium is incorporated into the glass product. Similar issues that could reduce the single pass retention in the LAW facility can also be assumed to impact the supplemental LAW flywheel.

B.4 SUPPLEMENTAL LOW-ACTIVITY WASTE FEED VECTOR UNCERTAINTIES

B.4.1 Volume to be Processed Through Low-Activity Waste Supplemental Treatment

In addition to the potential differences in the feed vector, evaluations are in progress that could change the way Hanford tank waste is processed. Rather than list each of the possible changes, many aspects of tank waste retrieval and immobilization should be assumed to change from the current assumptions. These changes have the potential to minimize the need for a single supplemental LAW treatment facility tied directly to the WTP, as assumed in this evaluation, and could potentially include smaller, modular systems designed to treat the waste at the individual tank farms or even individual tanks within a farm.

The throughput for the current WTP LAW Vitrification Facility is assumed to not likely change dramatically, as the models used in the Integrated Flowsheet contain most of the expected improvement in waste loading. Note that processing improvements in the WTP LAW Vitrification Facility may lead to improved capacity; however, this review determined that improvements would not likely eliminate the need for supplemental LAW treatment.

Changes in the required throughput of supplemental LAW could occur if the schedule for completion of LAW immobilization changes from the current assumptions. Note that acceleration of the mission is not a matter of building a larger scale immobilization facility; tank farms operations would need to be scaled similarly to allow retrieval of waste to meet the processing needs of the larger facility. If HLW processing is slower than expected, the need for supplemental LAW processing would decrease.

In addition, elimination of the WTP PT Facility would lead to direct feed options for HLW that may result in differences in the HLW washing and leaching operations. Changes to these processes would result in significant differences in the amount and composition of HLW effluents that comprise a sizable portion of the supplemental LAW feed.

Finally, all sludge wastes in the tank farms (except that expected to be classified as transuranic waste in the Integrated Flowsheet) are assumed to be retrieved and immobilized as HLW. Some initiatives are under consideration that could allow portions of the sludge tank waste to be classified and immobilized as LLW, but these changes were not considered during this review.

Therefore, the facilities for each immobilization technology will be sized as needed to process the feed vector at 360,000 gal/month. Regarding project costs, the results from this evaluation should be scalable such that the results can be used to evaluate the technology for supplemental immobilization of LAW.

B.4.2 Compositional Uncertainty

The composition of the feed vector from the Integrated Flowsheet has three major sources of uncertainty. First, the BBI is the source of the tank compositions used to create the feed vector. The uncertainty in BBI data has been evaluated previously (Peterson, 2016), along with the impacts of a 20% variation for selected components on the baseline process (RPP-RPT-51819, *Hanford Tank Waste Operations Simulator (HTWOS) Sensitivity Study*). The evaluation of uncertainty determined that 20% is not a bounding value, even for major analytes.

In addition, specific data for organic species are not provided by the BBI to allow assessments of the need for treatment to remove or destroy organic species prior to a grouting process. Selected RCRA metals, such as silver and barium, are considered supplemental analytes and data is available for only some of the wastes.

Second, the feed vector provided from the Integrated Flowsheet is based on proposed processing for retrievals and facility startup times that may change prior to supplemental LAW treatment startup. Retrieval and batch preparation experience at SRS has shown that compositions of the tanks can be different than expected and that operational issues can lead to frequent departures from the planned retrieval sequence (SRNL-STI-2013-00585, *SRS Sludge Batch Qualification and Processing: Historical Perspective and Lessons Learned*).

Third, the TOPSim model used to develop the feed vector has many simplifications as described above.

Note that the immobilization technologies have been previously evaluated over a wide range of compositions that may sufficiently cover the range of compositions expected from the Hanford SLAW feed vector. The analyses of each immobilization technology alternatives considered the composition variation in the feed vector.

B.5 MODULAR VARIANTS

The feed vector for supplemental LAW is best applied to a single on-site supplemental LAW treatment facility. Modular alternatives would shift the supplemental LAW processes to two or more locations and would not have the same feed vector. Thus, an evaluation of the compositions of the individual tank farms was performed to assess the impact of processing by farm or by tank with modular systems. This evaluation focused on grout as the immobilization process as modular vitrification or steam reforming facilities were deemed less suited to a modular approach. This evaluation used the BBI directly and includes additional organic data not included in the TOPSim model output. An example of this data is shown in Figure B-10 for the Hanford S Farm. A similar analysis was performed for each tank farm.

The plots in Figure B-10 contain the following information on the waste in the tanks. The data presented show the variation in composition between the tanks in a single farm. The values presented do not take into account any volume change during retrievals, any concentration changes due to volume increases in a final grout waste form, nor any removal of elements from the waste (e.g., cesium via TSCR).

Waste Form Performance Constituent Concentrations: This data is presented in both tabular and graphical form and lists the concentrations in the tanks of the main species in terms of waste form release (Tc, I, Cr, NO_2, NO_3, U). Note that the value for Tank S-102 comes from a solid and liquid retrieval line from the tank.

Grout Driver Constituent Concentrations: This data is presented in both tabular and graphical form and lists the concentrations in the tanks of the main species that could impact the formulation of a grout to immobilize the waste (Al, Ca, Na, PO_4 and SO_4).

Waste Phase Volume: This chart lists the current volumes of each of the three waste phases currently in the tanks (supernatant, saltcake, sludge).

Volume Increase to DST System: This chart lists the projected retrieved waste volume from each tank.

Waste Form Performance/Grout Driver Constituent Inventories by Waste Phase: Further detail on the Waste Form Performance and Grout Driver Constituents by showing their concentrations in the tanks split by waste phase.

RCRA Metal Constituent by Waste Phase: Presents the concentration of the eight RCRA metals by waste phase in the tanks.

Tank Waste Sampling History: The fourth page contains a chart to show the sampling history of each tank. Based on this information, a data quality ranking is provided based on RPP-RPT-54509, *One System – Hanford Tank Waste Characterization Vulnerability Assessment*, where the rating assigned to each analyte/component using BBI "Basis" field: Sample Based = 1, Calculation or Process Knowledge = 3, Template (Sample or Engineering) or no data = 5. Aggregate data quality ranking is weighted average by the analyte inventory in each component. This table can be used to assess uncertainty associated with the reported concentrations.

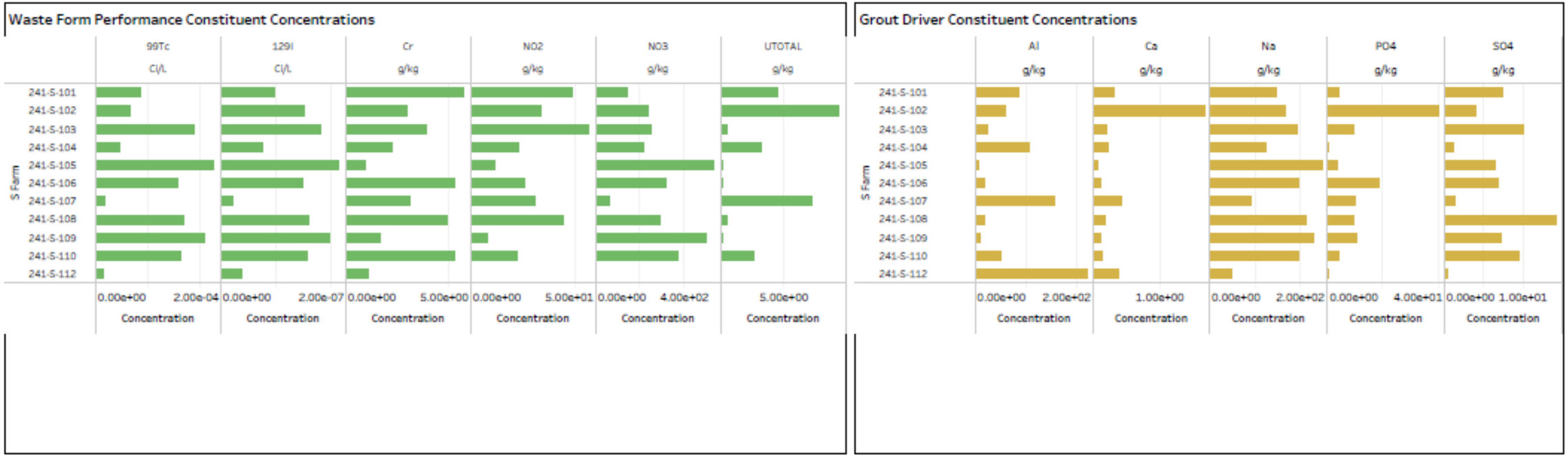
Sum of Fractions Plot: A sum of fractions plots for the full tank inventory (in the tanks) against Class A limits and Class C limits from 10 CFR 61.55, "Waste Classification," for both Table 1 and Table 2 components. The presented values do not include any removal from pretreatment of the waste upon retrieval. Plots are also presented for the sum of fractions assessment by waste phase.

Waste Form Performance Constituent Concentrations

S Farm	99Tc Ci/L	129I Ci/L	Cr g/kg	NO2 g/kg	NO3 g/kg	UTOTAL g/kg
241-S-101	8.51e-05	9.63e-08	5.74e+00	4.93e+01	1.44e+02	4.48e+00
241-S-102	6.58e-05	1.50e-07	2.95e+00	3.39e+01	2.38e+02	9.37e+00
241-S-103	1.88e-04	1.81e-07	3.94e+00	5.71e+01	2.53e+02	5.46e-01
241-S-104	4.70e-05	7.62e-08	2.27e+00	2.30e+01	2.15e+02	3.21e+00
241-S-105	2.27e-04	2.16e-07	9.45e-01	1.16e+01	5.37e+02	2.35e-01
241-S-106	1.57e-04	1.49e-07	5.27e+00	2.58e+01	3.19e+02	2.09e-01
241-S-107	1.76e-05	2.17e-08	3.13e+00	3.13e+01	5.92e+01	7.17e+00
241-S-108	1.69e-04	1.60e-07	4.87e+00	4.46e+01	2.95e+02	5.34e-01
241-S-109	2.08e-04	1.97e-07	1.70e+00	7.99e+00	5.04e+02	1.90e-01
241-S-110	1.62e-04	1.57e-07	5.30e+00	2.21e+01	3.71e+02	2.55e+00
241-S-112	1.53e-05	3.73e-08	1.08e+00	7.41e-03	2.04e-02	1.15e-02

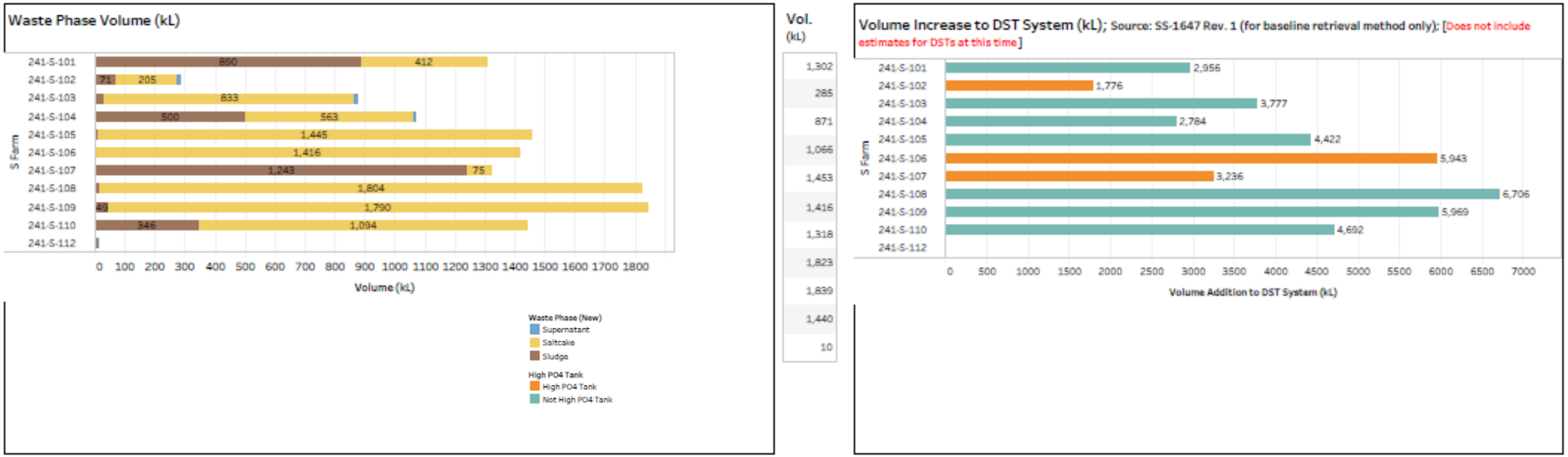
Grout Driver Constituent Concentrations

S Farm	Al g/kg	Ca g/kg	Na g/kg	PO4 g/kg	SO4 g/kg
241-S-101	8.58e+01	3.13e-01	1.47e+02	4.24e+00	7.51e+00
241-S-102	6.00e+01	1.67e+00	1.66e+02	4.00e+01	3.96e+00
241-S-103	2.56e+01	2.08e-01	1.91e+02	9.30e+00	1.01e+01
241-S-104	1.05e+02	2.31e-01	1.24e+02	5.67e-02	1.12e+00
241-S-105	6.80e+00	7.62e-02	2.47e+02	3.42e+00	6.48e+00
241-S-106	1.69e+01	1.12e-01	1.95e+02	1.87e+01	6.77e+00
241-S-107	1.56e+02	4.23e-01	9.01e+01	9.80e+00	1.27e+00
241-S-108	1.83e+01	1.81e-01	2.11e+02	9.58e+00	1.42e+01
241-S-109	8.45e+00	1.10e-01	2.28e+02	1.08e+01	7.29e+00
241-S-110	4.99e+01	1.51e-01	1.98e+02	4.09e+00	9.53e+00
241-S-112	2.19e+02	3.86e-01	4.82e+01	3.23e-01	3.17e-01



BBI Date: 8/12/2021; In-Tank vs. Retrieved Volume: Use In-Tank Vol.; Grout Vol. Increase: 1

Figure B-10. Concentration and Volume (As is) Dashboard (7 pages)



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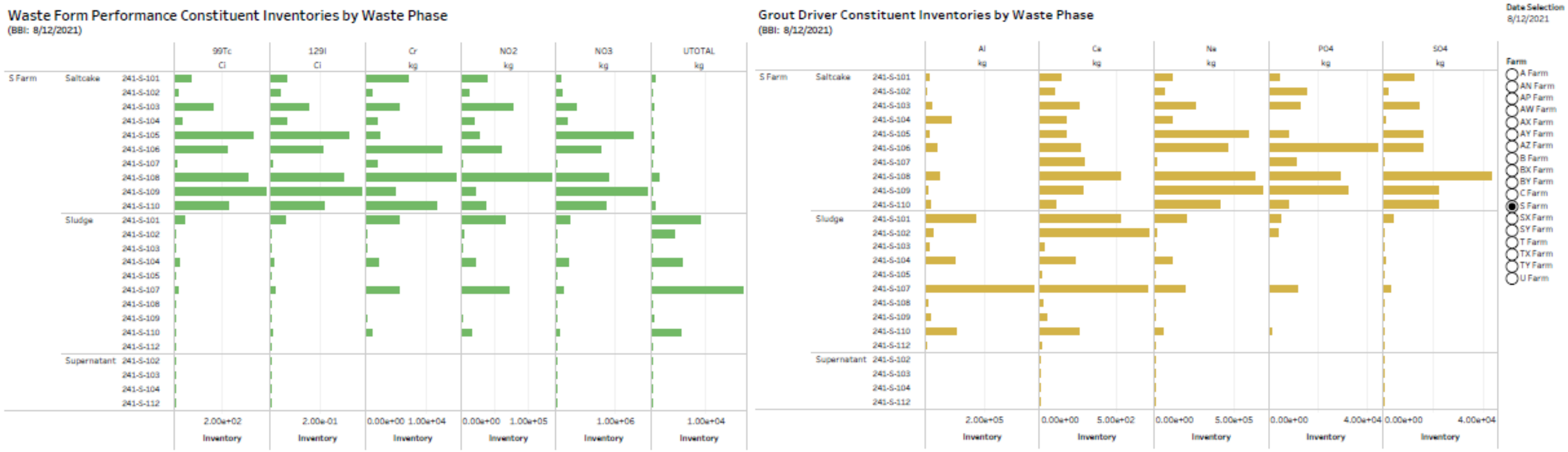
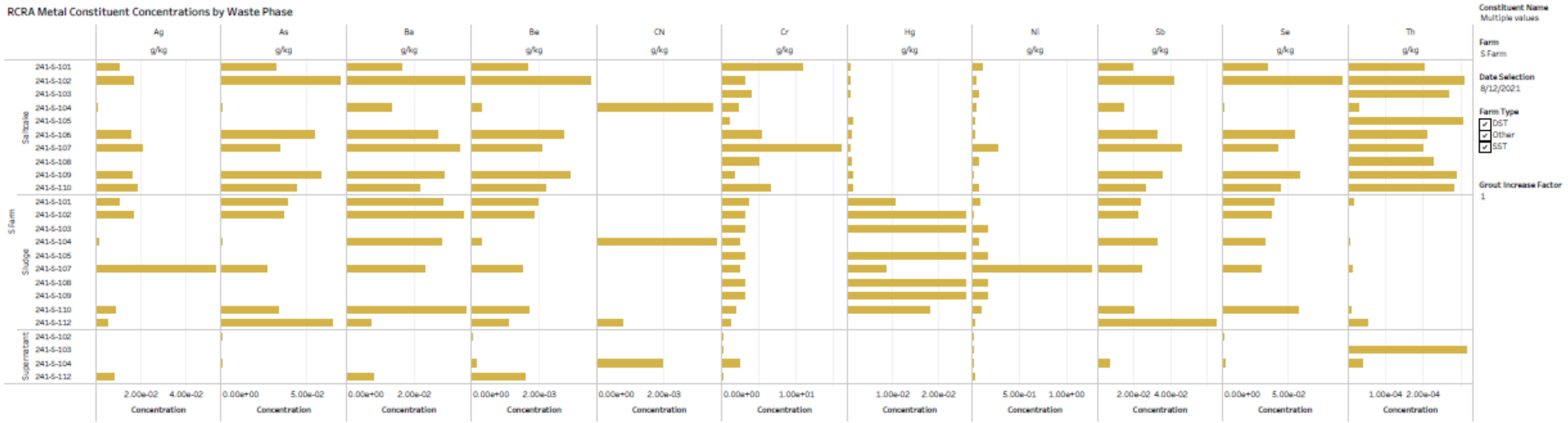


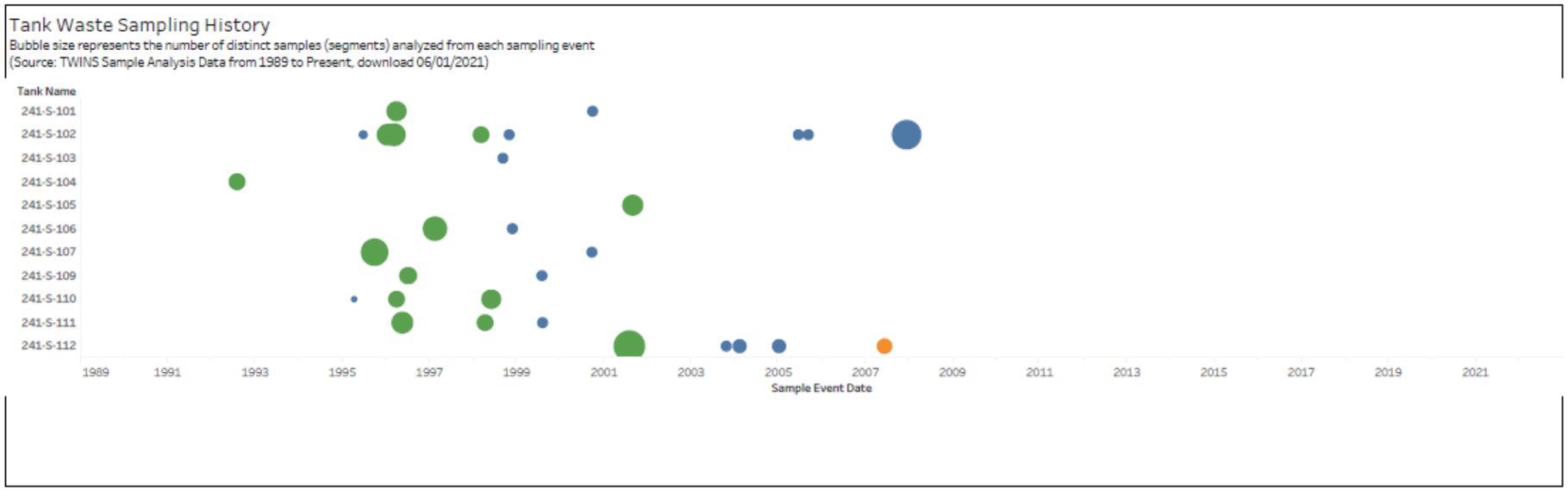
Figure B-10. Concentration and Volume (As is) Dashboard (7 pages)



RCRA Constituent Concentrations by Waste Phase

Farm		Ag g/kg	As g/kg	Ba g/kg	Be g/kg	CN g/kg	Cr g/kg	Hg g/kg	Ni g/kg	Sb g/kg	Se g/kg	Th g/kg
Saltcake	241-S-101	4.14e-02	1.28e-01	6.57e-02	6.55e-03		4.35e+01	2.10e-03	4.16e-01	7.71e-02	1.34e-01	8.09e-04
	241-S-102	1.63e-02	6.93e-02	3.49e-02	3.49e-03		3.03e+00	5.83e-04	3.23e-02	4.19e-02	9.03e-02	3.06e-04
	241-S-103						1.60e+01	2.32e-03	2.60e-01			1.06e-03
	241-S-104	1.41e-03	5.91e-04	2.66e-02	5.37e-04	6.93e-03	4.25e+00	2.90e-04	6.43e-02	2.85e-02	1.03e-03	5.80e-05
	241-S-105						1.87e+00	2.52e-03	4.71e-02			6.06e-04
	241-S-106	3.06e-02	1.08e-01	5.37e-02	5.37e-03		1.05e+01	1.75e-03	5.31e-02	6.46e-02	1.08e-01	4.15e-04
	241-S-107	6.15e-02	1.03e-01	1.00e-01	6.21e-03		4.80e+01	2.05e-03	8.09e-01	1.37e-01	1.24e-01	5.95e-04
	241-S-108						9.79e+00	1.91e-03	1.41e-01			4.52e-04
	241-S-109	3.24e-02	1.16e-01	5.81e-02	5.81e-03		3.33e+00	2.48e-03	2.52e-02	7.07e-02	1.16e-01	5.77e-04
	241-S-110	3.62e-02	8.67e-02	4.33e-02	4.33e-03		1.29e+01	2.30e-03	1.34e-01	5.20e-02	8.67e-02	5.58e-04
S Farm Sludge	241-S-101	1.04e-02	3.86e-02	2.84e-02	1.93e-03		3.59e+00	1.04e-02	8.06e-02	2.32e-02	3.86e-02	1.67e-05
	241-S-102	1.68e-02	3.66e-02	3.45e-02	1.83e-03		2.95e+00	2.61e-02	1.53e-02	2.20e-02	3.66e-02	1.15e-10
	241-S-103						2.96e+00	2.59e-02	1.63e-01			1.15e-10
	241-S-104	1.86e-03	4.81e-04	5.66e-02	5.58e-04	7.11e-03	4.83e+00	2.21e-04	1.43e-01	6.43e-02	6.29e-02	1.14e-05
	241-S-105						2.96e+00	2.60e-02	1.63e-01			1.15e-10
	241-S-107	2.11e-01	1.05e-01	9.33e-02	5.98e-03		9.80e+00	3.43e-02	5.05e+00	9.51e-02	1.17e-01	4.68e-05
	241-S-108						2.96e+00	2.60e-02	1.63e-01			1.15e-10
	241-S-109						2.96e+00	2.59e-02	1.63e-01			1.15e-10
	241-S-110	1.66e-02	6.75e-02	7.03e-02	3.37e-03		3.79e+00	3.63e-02	1.81e-01	4.05e-02	1.15e-01	1.39e-05
	241-S-112	5.45e-03	6.51e-02	7.44e-03	1.09e-03	7.80e-04	1.11e+00	4.21e-05	2.18e-02	6.51e-02		5.30e-05
Supernatant	241-S-102	0.00e+00	0.00e+00	0.00e+00	0.00e+00		0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
	241-S-103						1.86e-01	1.83e-04	8.28e-03			3.16e-04
	241-S-104	9.85e-05	4.26e-04	3.41e-05	1.36e-04	1.96e-03	2.46e+00	2.02e-04	1.64e-04	6.23e-03	1.54e-03	3.70e-05
	241-S-112	7.87e-03		7.87e-03	1.57e-03		7.82e-02	0.00e+00	3.16e-02			0.00e+00

Figure B-10. Concentration and Volume (As is) Dashboard (7 pages)

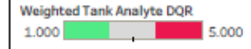


DQR for Constituents important to waste form performance

Farm	Tank Name	99Tc Ci	129I Ci	Cr kg	NO2 kg	NO3 kg	UTOTAL kg
S Farm	241-S-101	3.394	4.016	1.000	1.000	1.000	1.000
	241-S-102	3.197	3.139	2.454	2.425	2.889	1.132
	241-S-103	5.000	5.000	4.960	3.506	4.503	4.998
	241-S-104	1.938	5.000	1.000	1.000	1.000	1.104
	241-S-105	5.000	5.000	1.532	3.707	1.094	1.483
	241-S-106	5.000	5.000	1.000	1.000	1.000	1.001
	241-S-107	5.000	5.000	1.000	1.000	1.000	1.000
	241-S-108	5.000	5.000	5.000	5.000	5.000	5.000
	241-S-109	5.000	5.000	1.198	1.451	2.995	3.871
	241-S-110	5.000	5.000	1.000	1.000	1.000	1.000
	241-S-111	5.000	5.000	1.000	1.000	1.000	1.003
	241-S-112	1.000	1.000	1.005	1.000	1.000	1.000

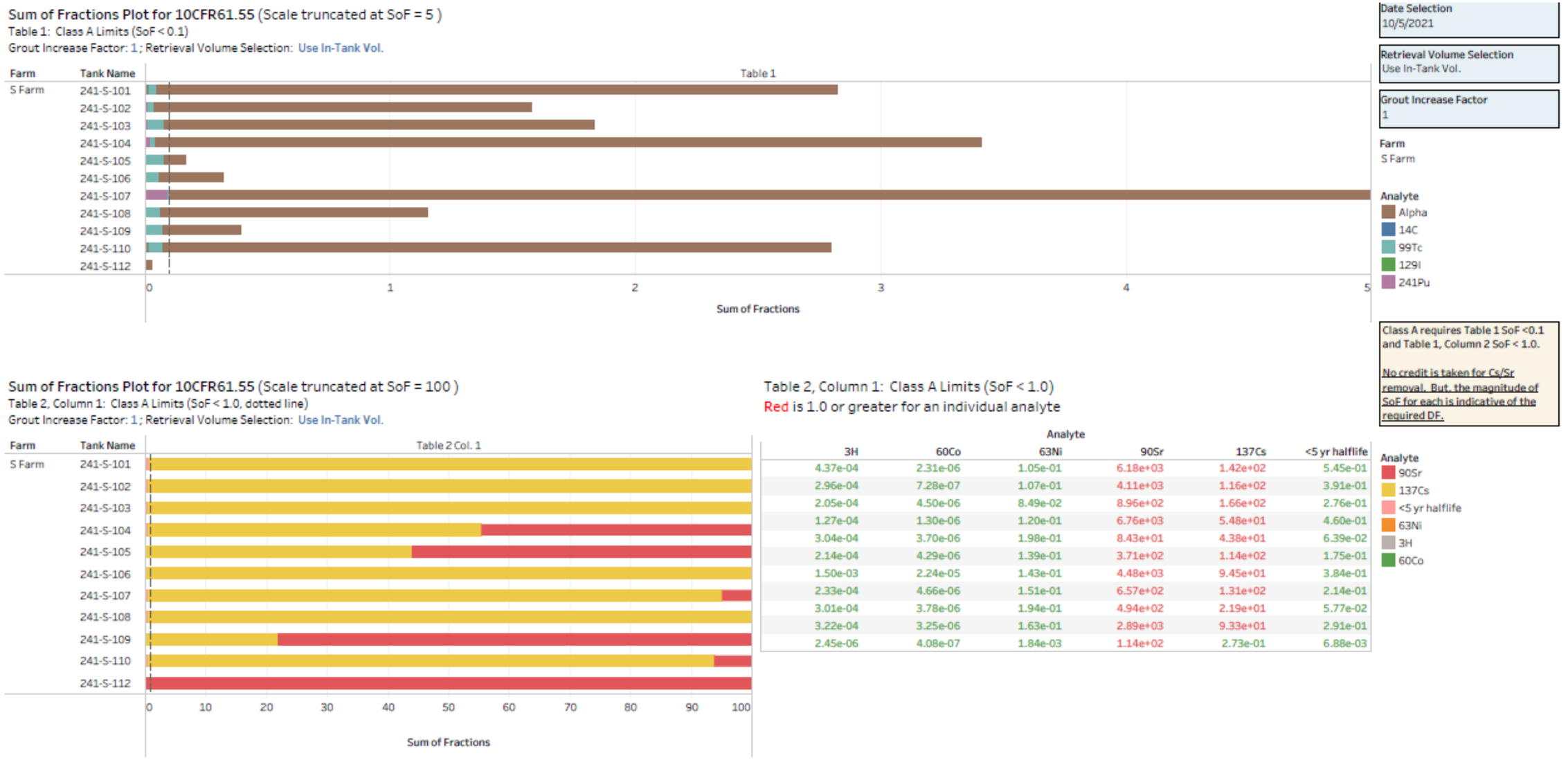
DQR for constituents important for grout formation

Farm	Tank Name	Al kg	Ca kg	Na kg	PO4 kg	SO4 kg
S Farm	241-S-101	1.000	1.000	1.000	1.000	1.000
	241-S-102	4.712	1.244	2.653	2.586	2.919
	241-S-103	4.272	4.832	4.307	4.812	4.706
	241-S-104	1.000	1.000	1.000	1.000	1.000
	241-S-105	3.044	1.375	1.250	1.258	1.149
	241-S-106	1.000	1.080	1.000	1.000	1.000
	241-S-107	4.974	1.000	1.000	1.000	1.000
	241-S-108	5.000	5.000	5.000	5.000	5.000
	241-S-109	3.522	1.559	1.050	1.044	1.019
	241-S-110	1.000	1.000	1.000	1.000	1.000
	241-S-111	1.000	1.000	1.000	1.000	1.000
	241-S-112	1.004	1.013	1.161	1.000	1.000



Rating method adapted from CS Smalley, One System - Hanford Tank Waste Characterization Vulnerability Assessment , RPP-RPT-54509 Rev. 01, October 13, 2014. Rationg assigned to each analyte/component using BBI "Basis" field: Sample Based = 1, Calcualtion or Process Knowledge = e, Template (Sample or Engineering) or no data = S. Aggregate DQR is weighted average by the analyte inventory in each component.

Figure B-10. Concentration and Volume (As is) Dashboard (7 pages)



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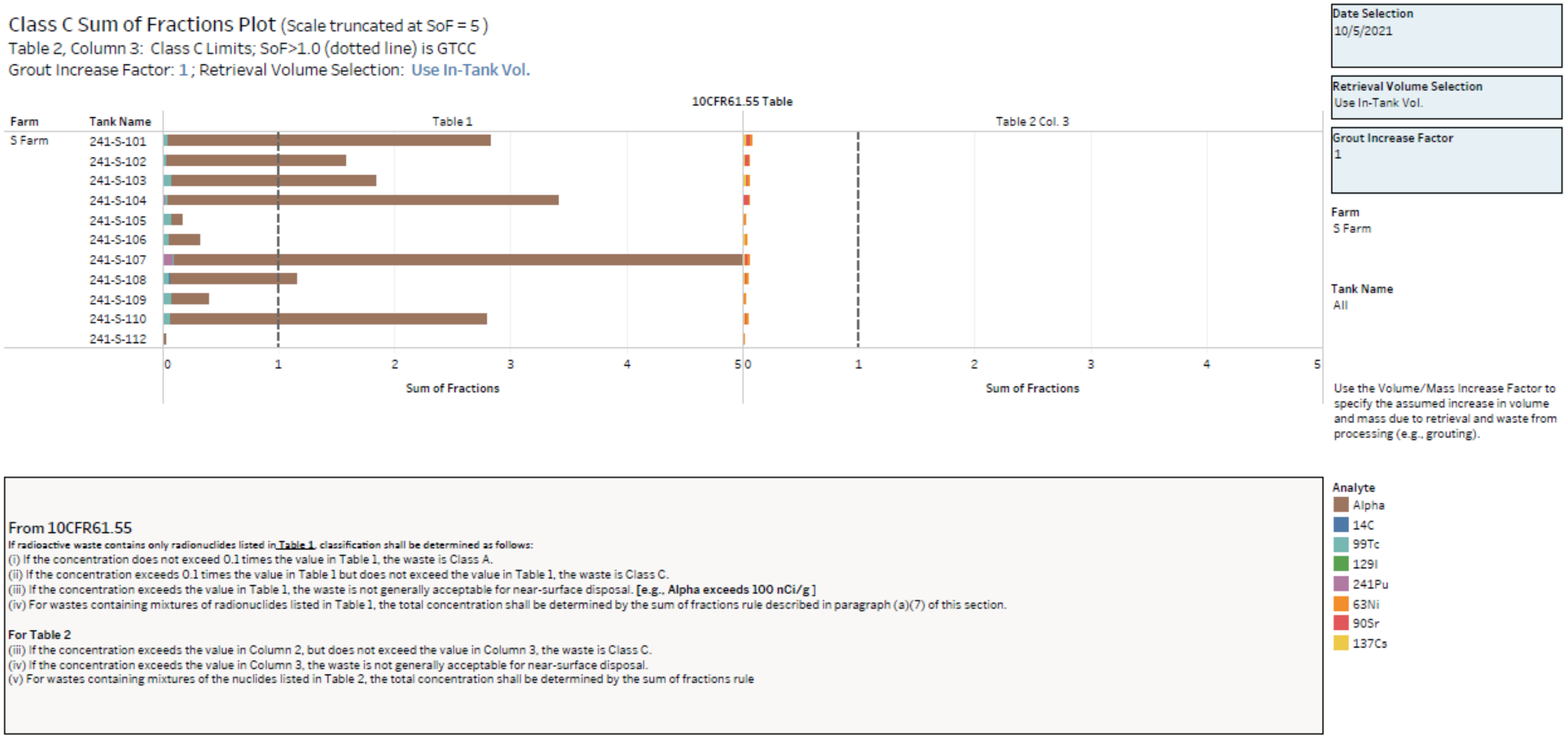

Figure B-10. Concentration and Volume (As is) Dashboard (7 pages)

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SRNL-STI-2013-00585, 2013, *SRS Sludge Batch Qualification and Processing: Historical Perspective and Lessons Learned*, Savannah River National Laboratory, Aiken, South Carolina.

SRNL-STI-2018-00499, 2018, *Results for the Second Quarter Calendar Year 2018 Tank 50 Salt Solution Sample*, Savannah River National Laboratory, Aiken, South Carolina.

SRNL-STI-2020-00582, 2021, *Hanford Supplemental Low Activity Waste Simulant Evaporation Testing for Removal of Organics*, Rev. 0, Savannah River National Laboratory, Aiken, South Carolina.

Appendix C. Alternative Descriptions and Associated Assumptions

C.1 INTRODUCTION

The alternatives for supplemental immobilization of low-activity waste (LAW) are divided into three technologies: vitrification, steam reforming, and grouting. This appendix provides an overview of each of the technologies and their assumptions, with schematics depicting the building blocks of each alternative.

All of the alternatives considered in this evaluation are shown in Table C-1. Generally, an alternative is assigned a number for different types of facilities (e.g., single vs. modular), followed by a letter if the facility is on-site (A) disposal or off-site (B) disposal of the primary waste form, if applicable. Another letter is assigned if an additional treatment ("C" for technetium/iodine removal) or activity ("D" for analysis and diversion) is needed. Vitrification is assumed to only result in on-site (Integrated Disposal Facility [IDF]) disposal of the primary waste form. All on-site immobilization alternatives assume on-site (IDF) disposal of secondary solid wastes. Several of the alternatives screened out for various reasons were not fully evaluated in the taxonomy, with the reasons provided in the individual detailed descriptions below. All alternatives include continued operation of the first set of LAW melters in the Hanford Waste Treatment and Immobilization Plant (WTP). In some alternatives, waste that is found to be incompatible with the immobilization method would be diverted to the WTP LAW melters.

The alternatives were formulated based on the National Defense Authorization Act for fiscal year (FY) 2017 (NDAA17) report (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*) and expanded to include other versions of those alternatives as conceived by team members or drawn from recently developed concepts. Only immobilization methods that are of relatively high technical maturity and had (1) been demonstrated with comparable tank waste elsewhere at laboratory scale or larger; (2) been demonstrated at large scale with radioactive streams albeit with different waste feed compositions; and (3) evidence that they could pass the basic criteria, such as meeting Resource Conservation and Recovery Act (RCRA) criteria for hazardous metals, were considered.

Table C-1. Brief Title and Description of Alternatives

Alternative designation	Alternative title	Brief description	Full evaluation completed
No action	No Action	Operate WTP LAW melters only (no additional facility)	No
Vitrification 1	Single Vitrification Plant	Construct additional melter facility	Yes
Vitrification 2	Increased LAW Vitrification Rate	Operate WTP LAW melters only, but take steps to increase vitrification rate	No
Vitrification 3	Near-Tank Vitrification	Construct modular vitrification facilities/ melters near waste tanks	No
FBSR 1A	Fluidized Bed Steam Reforming – On-site Disposal	Construct FBSR facility; dispose monolith waste form onsite	Yes
FBSR 1B	Fluidized Bed Steam Reforming – Off-site Disposal	Construct FBSR facility; dispose granular waste form offsite	Yes
FBSR 2A	Modular Fluidized Bed Steam Reforming – On-site Disposal	Construct FBSR facilities; dispose monolith waste form onsite	No
FBSR 2B	Modular Fluidized Bed Steam Reforming – Off-site Disposal	Construct FBSR facilities; dispose granular waste form offsite	No
Grout 1A	Single Grout plant – On-site Disposal	Construct single grout plant in 200 East Area; dispose containerized grout in IDF	Yes
Grout 1B	Single Grout plant – Off-site Disposal	Construct single grout plant in 200 East Area; dispose containerized grout offsite	Yes

Table C-1. Brief Title and Description of Alternatives

Alternative designation	Alternative title	Brief description	Full evaluation completed
Grout 2A	Separate Grout Plants for 200 East and West Areas – On-site Disposal	Construct grout plants in 200 East and West Areas; dispose containerized grout in IDF	Yes
Grout 2B	Separate Grout Plants for 200 East and West Areas – On-site Disposal	Construct grout plants in 200 East and West Areas; dispose containerized grout offsite	Yes
Grout 3A	Individual Grout Plants for Each Tank Farm or Tank Farm Group – On-site Disposal	Construct multiple modular grout plants in 200 East and West Areas; dispose containerized grout in IDF	No
Grout 3B	Individual Grout Plants for Each Tank Farm or Tank Farm Group – Off-site Disposal	Construct multiple modular grout plants in 200 East and West Areas; dispose containerized grout offsite	No
Grout 4A	Off-site Vendor for Grouting – On-site Disposal	Ship liquid to off-site vendor for grouting; dispose containerized grout in IDF	Yes
Grout 4B	Off-site Vendor for Grouting – Off-site Disposal	Ship liquid to off-site vendor for grouting; dispose containerized grout offsite	Yes
Grout 5A	Single Grout Plant – On-site Monolith in Vault Disposal	Construct single grout plant in 200 East Area; dispose a monolith of grout in vaults	Yes
Grout 5B	Single Grout Plant – On-site Containers in Vault Disposal	Construct single grout plant in 200 East Area; dispose containerized grout in vaults	Yes
Grout 1C	Single Grout Plant with Technetium/ Iodine Removal and On-site Disposal	Remove ^{99}Tc and ^{129}I, followed by Grout 1A	Yes
Grout 2C	Separate Grout Plants for 200 East and West Areas with Technetium/Iodine Removal with On-site Disposal	Remove ^{99}Tc and ^{129}I, followed by Grout 2A	Yes
Grout 1D	Single Grout Plant with Technetium/ Iodine Sample-and-Send with Off-site/On-site Disposal	Analyze LAW; grout all; select on-site or off-site disposal of container based on ^{99}Tc and ^{129}I content	Yes
Grout 2D	Grout 2A + Sample Technetium/ Iodine/Send Offsite/Onsite	Analyze LAW; grout all in modular plant; select on-site or off-site disposal of container based on ^{99}Tc and ^{129}I content	No
Grout 6	Phased Off-site and On-site Grouting in Containers	Phased approach of off-site vendor grouting and off-site disposal, followed by on-site grouting and on-site disposal	Yes

^{99}Tc = technetium-99.
^{129}I = iodine-129.
FBSR = fluidized bed steam reforming.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
WTP = Waste Treatment and Immobilization Plant.

WRPS performed TOPSim simulations to estimate the annual costs of construction and operations for an alternative similar to Vitrification 1 and an alternative similar to Grout 4B – referred to here as "Vitrification 1 (modified)" and "Grout 4B Early Off-site Disposition". Those model runs cover the entire Hanford tank waste mission (high-level waste [HLW], LAW, plus LAW supplemental treatment) (Table C-2). Details of the mission analysis parameters are described in more detail in Volume II, Appendix F.

Table C-2. TOPSim Hanford Tank Waste Mission Analyses

Simulation designation	Mission Analysis Title	Brief description
Vitrification 1 (modified)	Single Vitrification Plant – Modified (MR-50638[a])	Construct additional melter facility – 2050 start
Grout 4B (early off-site disposition)	Off-site Vendor for Grouting – Off-site Disposal (MR-50713[b])	Ship liquid to off-site vendor for grouting; dispose containerized grout offsite

[a] MR-50638, 2021, *Analysis of Alternatives (AoA) Scenario Alternative 18 Phased Startup*, Rev. 0, Washington River Protection Solutions, LLC, Richland, Washington.

[b] MR-50713, 2022, *NDAA LAWST Modeling Study*, Rev. 0, Washington River Protection Solutions, LLC, Richland, Washington.

Pretreatment

All LAW is assumed to be pretreated to remove ^{137}Cs equivalent to or beneath the WTP LAW Vitrification Facility criteria (<3.18E-5 Ci/mole Na^+ [PNNL-28958, *Cesium Ion Exchange Testing Using a Three-Column System with Crystalline Silicotitanate and Hanford Tank Waste 241-AP-107*]), which is sufficient to permit contact-handled maintenance in all subsequent processes. This level is also assumed for grouting and fluidized bed steam reforming (FBSR) alternatives. In all alternatives, the liquid tank waste is assumed to be processed through the Tank Farms Pretreatment (TFPT) process or similar system(s). Pretreatment in WTP does not preclude any alternatives but may impact the final waste classification. Note that this ^{137}Cs concentration would be ~0.2 Ci/m^3, well beneath U.S. Nuclear Regulatory Commission (NRC) Class A low-level waste (LLW) limits (1 Ci/m^3) (10 CFR 61.55, "Waste Classification") for waste at 6 M [Na^+]. Substituting crystalline silicotitanate (CST) for the elutable spherical resorcinol-formaldehyde resin in WTP was not considered in this evaluation due to the substantial facility redesign, added cost, and concomitant delays that would be needed to handle a non-elutable media within the WTP Pretreatment Facility. However, ultimately, the need for, method, and location of pretreatment will be evaluated by the U.S. Department of Energy (DOE) on a case-by-case basis, consistent with DOE O 435.1, *Radioactive Waste Management*.

The TFPT is a follow-on facility, as described in ORP-11242, *River Protection Project System Plan* (System Plan, Rev. 9) and is similar to the tank-side cesium removal (TSCR) system. Using TFPT removes ^{137}Cs, ^{90}Sr, and some actinides using CST.[1] The concentration of the feed to the TFPT system would be as high as 6 M [Na^+], but selected feeds may be processed for cesium removal at lower concentrations (e.g., some feeds may be processed at ~2 M [Na^+] to maintain phosphates in solution to prevent plugging the filters).

The simplified schematic of the TFPT process is shown in Figure C-1. The schematic shows a filter followed by three CST columns in series, although the number of columns in series may change, depending on processing needs. The untreated tank waste is adjusted in the double-shell tank (DST) to the target concentration, processed through the TFPT, and the decontaminated liquid is stored in an interim storage tank prior to immobilization in the supplemental LAW treatment process. Solids that collect on the filter are periodically flushed back to the DST. The waste is pumped through the columns until the ^{137}Cs breakthrough is detected, then the columns are flushed with water and replaced with fresh columns.

[1] Crystalline silicotitanate (CST) is used as a common descriptor of the engineered bead form of the media produced by Honeywell UOP of Des Plaines, Illinois, and is designated as Ionsiv™ 9120-B or 9140-B.

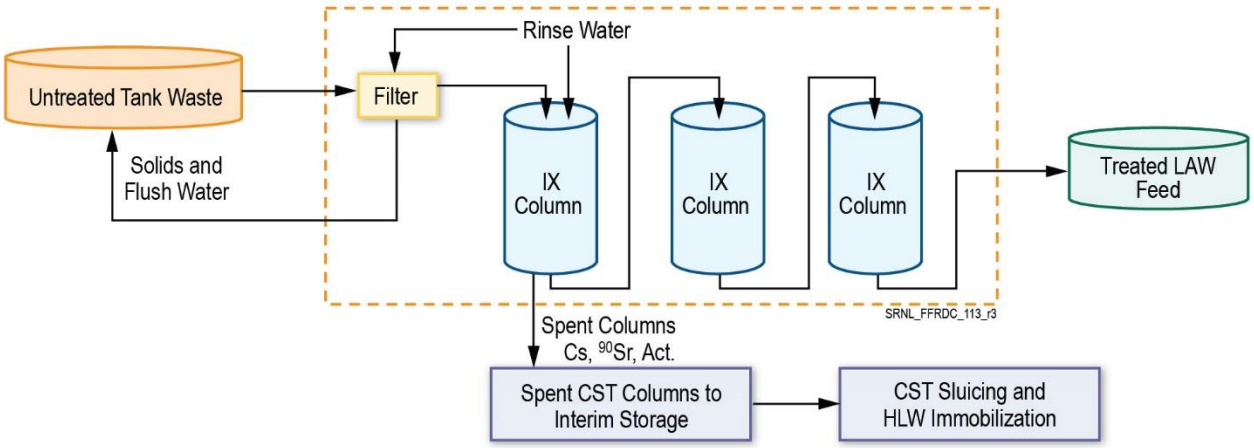


Figure C-1. Tank Farms Pretreatment Process

The spent CST columns from TFPT are interim stored onsite. Vitrification of the spent CST is the assumed disposition path. The spent CST is assumed to be sluiced from the columns and sent for vitrification with HLW once that facility begins operation. The equipment needed to sluice (and potentially to grind) the spent CST is not designed but would presumably be smaller than the existing TSCR system because it would need to only contain one column at a time and its only function is to sluice the material out (and possibly grind it) before transporting the waste to a DST or the WTP. The number of columns of spent CST (~600 kg each) was estimated in System Plan (ORP-11242, Rev. 9) at 751 columns if it was used to process all liquid waste.

The TOPSim model run performed to support the cost and schedule projections used in this report indicated up to ~1,000 columns would be needed, with the difference of ~250 columns due to differences in the volume and composition of HLW wash water. The 1,000 columns would bound the number of columns needed, because minimizing the number of columns needed was not optimized in this model run and the earlier run indicated ~250 columns fewer. Several efficiencies would likely be identified if this scenario is pursued, such as optimum column operating parameters, waste evaporation concentrations, and feed sequencing. Reuse of columns after sluicing out the spent CST is also not included in the cost assumptions, but presumably could be pursued once the HLW Vitrification Facility is operational and a CST disposal path is established. Sluicing out the CST does not decrease the quantity of spent CST columns produced and thus vitrified, only allows reuse of the column equipment to reduce cost. This quantity of spent CST represents ~2.7 wt% of the mass of HLW glass that would be produced, and this amount is expected to be accommodated in the glass formulations (ORP-61830, *Final Report: Vitrification of Inorganic Ion-Exchange Media, VSL-16R3710-1*). This quantity of spent CST is not expected to impact the total quantity of HLW glass that would be produced based on that testing. The CST is essentially a replacement of some of the glass-forming minerals that are included in the HLW glass formulation.

The extent of removal of soluble ^{90}Sr and actinides by CST is not known for all feed stream compositions but is estimated to be 99% and 30%, respectively, unless the waste is a complexant waste. The estimate for non-complexant waste is based on limited testing of processing Tanks AW-102, AP-107, and AP-105 through columns of CST (PNNL-28783, *Dead-End Filtration and Crystalline Silicotitanate Cesium Ion Exchange with Hanford Tank Waste AW-102*; PNNL-27706, *Cesium Ion Exchange Testing Using Crystalline Silicotitanate with Hanford Tank Waste 241-AP-107*; and PNNL-30712, *Ion Exchange Processing of AP-105 Hanford Tank Waste through Crystalline Silicotitanate in a Staged 2- then 3-Column System*). These tanks contain blends of supernatant liquid from several tanks and are expected to be representative of the strontium chemistry in non-complexant wastes. The $SrOH^+$ ion is the species known to be removed by CST (Zheng, 1996) and is present in non-complexant wastes. Complexant waste could contain high soluble ^{90}Sr and actinides that may or may not be in the form that is removed by CST.

The distribution coefficient for non-complexed ^{90}Sr is approximately 10 times higher than for cesium on CST (SRNL-STI-2019-00678, *Preliminary Determination of the Impact of Alkaline Earth Metals on Crystalline Silicotitanate*, and PNNL-30185, *Crystalline Silicotitanate Batch Contact Testing with Ba, Ca, Pb, and Sr*), which indicates that removal of ^{90}Sr would normally exceed that for cesium during the TFPT column operation. Further, the laboratory testing with non-complexant waste from Tanks AW-102 (PNNL-28783), AP-105 (PNNL-30712), and AP-107 (PNNL-27706) indicated that the ^{90}Sr concentration in the column effluent (i.e., all were <1E-3 μCi/mL) would also be beneath the corresponding NRC LLW Class A limit (0.04 Ci/m^3), and the combined plutonium isotope concentrations were beneath the Class A limit (100 nCi/g).

These CST column tests indicate that 99.8–99.9% removal of strontium is achievable with non-complexant wastes. The tests also indicate that >50% of the plutonium and neptunium isotopes would also be removed. The ability of CST to remove strontium has been known since its invention (Zheng, 1996), and its absorption is included in the computer model (ZAM) developed by its inventors. Verification of the ability of CST to remove these isotopes to beneath the Class A limit for each specific tank or batch could be part of the waste acceptance criteria for the immobilization process, if applicable. The Federally Funded Research and Development Center (FFRDC) NDAA17 report (SRNL-RP-2018-00687) indicated that 90% of waste would reach Class A if 99% of the soluble ^{90}Sr was removed.

The assumed pretreatment with TSCR/TFPT columns to remove ^{137}Cs also results in an estimated removal of 99% of soluble ^{90}Sr from non-complexant LAW. The benefit of creating a Class A waste form is that it increases the off-site disposal options for non-complexant LAW. Only two tanks are believed to contain complexant waste, Tanks AN-102 and AN-107, and the planned treatment involves a separate strontium/transuranic (Sr/TRU) removal process that uses strontium isotopic dilution for ^{90}Sr and sodium permanganate for the actinides (RPP-PLAN-51288, *Development Test Plan for Sr/TRU Precipitation Process*). That Sr/TRU process, along with CST treatment is likely to result in a Class B waste, limiting off-site disposal to Waste Control Specialists, LLC (WCS) only if grouted. Presumably, this waste would be sent to LAW vitrification due to the high organic content if it is not compatible with grouting. Conversely, pretreatment in WTP does not remove soluble ^{90}Sr because it uses a different ion exchange media. Pretreatment in WTP would result in a larger portion of the liquid waste being Class B, limiting off-site LAW disposal of that portion to only WCS in Texas.

After pretreatment, the liquid will be evaporated to remove excess water; with many of the organic species in the waste expected to partition to the condensate during that evaporation. The condensate containing the soluble organics will be sent to the Effluent Treatment Facility (ETF), which is permitted for destruction of the organics in tank farms evaporator condensate. The target sodium ion concentration for evaporation has not been specified but could be as high as 9 M [Na^+] for selected wastes. Many of the Land Disposal Restriction (LDR) organic compounds suspected to be in the waste would likely be removed to concentrations below the treatment standard by the evaporation process (SRNL-STI-2020-00582, *Hanford Supplemental Low Activity Waste Simulant Evaporation Testing for Removal of Organics*; RPP-RPT-63493, *Tank Waste LDR Organics Data Summary for Sample-and-Send*; and SRNL-STI-2021-00453, *Potential for Evaporation and In Situ Reaction of Organic Compounds in Hanford Supplemental LAW*). Of the liquid tank sample data in the Tank Waste Information System (TWINS), no tanks were identified that were confirmed to contain a nonvolatile[2] organic above the non-wastewater regulatory limit, although many tanks do not have reported analysis results. Further, of the 132 regulated organics potentially present in tanks, 109 of those are sufficiently volatile to be removable by evaporation (i.e., have Henry's Law coefficients above the estimated lower limit currently set by n-nitrosomorpholine).

[2] Non-volatile is defined as less volatile than n-nitrosomorpholine that was shown removable by evaporation from simulated tank supernatant liquid.

Recent experimental work expanded the list of organic compounds that could be removed by atmospheric pressure evaporation (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*), including n-nitrosomorpholine, and identified some regulated species that were not stable in caustic LAW simulant under test conditions. Testing also demonstrated that some key species that are not removable by evaporation, including phenolics, were treatable by oxidation with permanganate in simulated LAW. Another recent report that further investigated the TWINS data (RPP-RPT-64064, *Distribution of LDR Organic Compounds in Hanford Tanks Waste and the Implications to LAW Treatment by Cementitious Solidification/Stabilization*) indicates that without any LDR removal process, thirteen tanks would produce a grout waste form that would exceed the non-wastewater standard for LDR organics. However, in eight of these tanks, the exceeding compounds are either n-butanol, n-nitrosomorpholine, or toluene, which are all predicted to be susceptible to removal by evaporation. The exceedances in the remaining five tanks are associated with polychlorinated biphenyls (PCB). However, the calculated PCB concentrations in staged waste from these five tanks would be above the water solubility limits for PCBs, indicating that these compounds would not be completely soluble at these levels. Rather, PCBs would be associated with either a separate organic phase or absorbed onto retrieved, undissolved solids. In either case, the undissolved PCBs would be removed by the filter system associated with the TSCR/TFPT process. If only dissolved PCBs are present in the liquid sent for grouting, then the concentration in the solidified waste form would be below the PCB non-wastewater standard of 10 mg/kg. The solids and insoluble PCBs removed by filtration would be sent for processing with the sludge in WTP and would not be grouted.

The conclusions about the LDR organics in tank waste are not a complete representation of all LAW because organic analysis results are not available for all tanks, and many of the results are from samples collected years ago. However, the data that is available was evaluated and indicates that much of the LAW would produce a compliant cementitious waste form even without organic removal.

While not a specific technology, the ability of a supplemental LAW immobilization process to have flexible processing rates either through the ability to turn-down the process or the ability to easily stop and start (idle) the process is important. The processing of HLW and the variable amounts of salt in tanks being retrieved causes a wide range of flow rates for supplemental LAW treatment, depending on the need for washing and leaching cycles of a particular sludge. Having the capacity to process at higher-than-average flow rates or to turn off the process and readily resume processing would be beneficial.

The primary alternatives are shown in Table C-3 (Section C.1.5), along with (1) whether the cross-site supernatant liquid transfer line is needed to support the alternative,[3] (2) whether the DSTs are used to prepare and stage the LAW liquid, (3) an indication of the primary waste form disposal location, and (4) whether the waste form is individual containers or a single vault. These alternatives are described in the sections that follow the table.

C.1.1 Vitrification Alternatives

The vitrification process was described in the FFRDC NDAA17 report (SRNL-RP-2018-00687), and any updates are included in the vitrification alternatives descriptions in the following section. In general, vitrification blends radioactive liquid waste with glass-forming materials at high heat in a ceramic-lined Joule-heated[4] melter, forming a molten mixture that is poured into stainless steel containers to cool and solidify into a borosilicate glass waste form that is highly stable in the expected conditions in a disposal facility.

[3] Note that the transfer line is not needed for waste that is compatible with grouting but may be needed for other purposes, such as waste retrieval or transfer to WTP.

[4] Electrical current is passed through the molten glass between electrodes. The electrical resistance of the molten glass results in heat generation.

Vitrification technology has been used in the U.S. and other countries to treat the high-activity fraction of tank waste, which is generally made up of a dilute salt solution in a slurry with metal oxides and hydroxides, not a concentrated salt solution. Both Savannah River Site (SRS) and the West Valley Demonstration Project use(d) vitrification to immobilize metal oxide/hydroxide slurries from tanks.

Waste vitrification technology of Hanford LAW consists of mixing a chemically characterized, aqueous waste stream with sugar (an organic reducing agent), specific metal oxides, and metal carbonates to produce a slurry that is fed to a melter in which the slurry is incorporated into the melt pool. The volatile components are driven into offgas by heat, requiring a complex offgas system to treat the melter offgas prior to discharge and generating two secondary liquid waste streams and a solid secondary waste that also requires treatment.

All water is vaporized from the melter into the offgas system, which typically has scrubbers and a condensate system that generates a liquid waste stream that is larger in volume than LAW feed to the facility. The sulfate ion in the LAW feed is one of the most challenging species because it has low solubility in the glass and can limit the waste loading. Secondly, excess sulfur in the melter causes layers of corrosive materials that can reduce melter and equipment lifetime. The nitrates and nitrite salts are converted to nitrogen oxides (NO_x) by reaction with a reductant, such as sugar. The NO_x must be destroyed before the vapors are released to the atmosphere. Organic chemicals present in the waste are destroyed by the heat of the melter, but some others can be produced by incomplete reaction of the sugar. The mercury, ^{99}Tc, and ^{129}I are largely vaporized in the melter and collect in the offgas system. In the current WTP LAW melters, the offgas condensates are expected to be recycled in an attempt to increase retention of the ^{99}Tc and ^{129}I. More detail is provided in the individual vitrification alternative descriptions (Sections C.3, C.4, and C.5).

Three vitrification alternatives were considered in this evaluation, with differences reflecting different approaches in the LAW supplement treatment facility location or integrating process improvements. These alternatives are shown in Table C-1.

C.1.2 Fluidized Bed Steam Reforming Alternatives

The FBSR process was described in the NDAA17 report (SRNL-RP-2018-00687), and any updated information since its publication is included in the FBSR alternatives descriptions in Sections C.6 and C.7. FBSR can convert radioactive liquid waste to a dry, granular mineral product. With proper controls, the mineral product consists of chemical structures that can retain radionuclides and other constituents of concern. FBSR has been researched, developed, and used commercially for over two decades for processing low-level radioactive wastes, although those applications are unlike the high sodium ion content, alkaline Hanford tank waste.

FBSR operates at temperatures up to 725–750°C to evaporate water in the waste, destroy organics, destroy nitrates, and convert the solid residue into a durable, leach-resistant waste form. Coal and oxygen are fed into the vessel known as the denitration and mineralizing reformer (DMR) where they react in the presence of high temperature steam (supplied at 500–600°C) under chemically reducing (pyrolytic) conditions to heat the DMR and produce low concentrations of hydrogen and other reduced gas species.

The DMR contains a bed of particles that are the right size and density to be continually fluidized by steam that flows upward through the bed. The liquid tank waste is mixed with clay, and the slurry is sprayed into the bottom of the vessel. Nitrates and nitrites in the waste react primarily with steam and hydrogen under the chemically reducing conditions and destroyed with relatively high efficiencies (up to 99%). Organic chemicals in the tank waste are pyrolyzed or otherwise destroyed by the heat. Mercury in the waste feed vaporizes and is captured in the offgas system. The ^{99}Tc and ^{129}I are largely retained in the mineral waste form with high single pass efficiencies, and any that escapes is captured in the offgas system and recycled into the DMR to improve retention in the mineral waste form.

No liquid waste is discharged from the FBSR system, as the system is operated such that all of the water is recycled to the DMR and eventually vaporized, treated in the offgas system, and then discharged to the atmosphere. Further details are provided in the FBSR alternatives descriptions (Sections C.6 and C.7).

FBSR has been used internationally and in the United States at a commercial facility for stabilizing ion exchange media. A FBSR facility, the Integrated Waste Treatment Unit (IWTU), has been constructed at the Idaho Nuclear Engineering Technology Center (INTEC) at the Idaho National Laboratory (INL) to stabilize approximately 900,000 gallons of acidic liquid tank wastes. The design of the facility was informed by large-scale testing at a separate test facility, and simulant test runs are being conducted at the facility.

Four FBSR alternatives were considered, with the differences relating to using a single facility or multiple facilities, and the waste form disposal location.

C.1.3 Grout Alternatives

Extensive experience using grout waste forms has been gained in the U.S. from federal and commercial applications and as the standard immobilization technology for LLW across the international community. This experience includes grouting of the supernatant liquid portion of the tank waste at SRS[5] after treatment of the waste to remove soluble cesium, strontium, and actinides. At SRS, the grouted waste is disposed in large on-site vaults adjacent to the Saltstone facility.

As no definitive formulation has been designated for the immobilization of supplemental LAW at Hanford, in either a containerized or vault waste form, general assumptions regarding the components of a grout formulation were made. Information on candidate dry reagents, material availability, and formulation development to date at Hanford is provided in Volume II, Appendix A. The grout was assumed to have a water to dry mix ratio between 0.4 – 0.6 to ensure adequate waste loading and to fall within the commonly tested range. However, different ratios are plausible. The grout was also assumed to be electrochemically reducing through the inclusion of blast furnace slag, which has a long history of ensuring grout waste forms are compliant with regulatory requirements for hazardous metals as measured by the toxicity characteristic leaching procedure (TCLP) test, and to improve technetium retention by reduction to an insoluble species.

The required properties of the grout waste form in each alternative are dictated by the disposal location (e.g., zero potable water pathway), the immobilization facility used (modular or centralized plant), and chemistry of the waste. A history of experience in grout waste forms both nationally and internationally, descriptions of immobilization facilities/technologies relevant to the alternatives, performance requirements and formulation considerations based on disposal locations, recent work since the NDAA17 report (SRNL-RP-2018-00687), and key assumptions are presented in Volume II, Appendices A, G, and L.

The grouting process for each alternative may be different, depending on both the process selected and the supernatant liquid composition. The basic components are ordinary Portland cement (OPC), blast furnace slag (BFS), and fly ash (FA). Other additives may be used or ratios may vary, depending on composition and disposal requirements. The ratio of the basic components and waste loading will vary, depending on whether the grout must be pumped long distances to a vault or would be transferred to a nearby container because the rheological properties and set-time needs would be different. The dry ingredients would likely be stored in silos exterior to the grout plant and fed into a dry mix blend tank inside the facility and then to a dry feed hopper.

[5] While some differences exist between the SRS and Hanford wastes, the SRS waste is the closest analog in the U.S. to the waste at the Hanford Site.

The baseline for all grout alternatives is to design all aspects of the system to meet the waste acceptance criteria for disposal at the specified disposal site using the integrated retention properties of the waste form chemistry, container (if applicable), disposal environment (e.g., IDF, vault, or offsite), and geotechnical cap. The intent is to design the entire system to be protective of the environment and retain the contaminants of concern to within the applicable limits. Additional measures, such as barriers and getters, may be taken to provide additional confidence of contaminant retention. The details of those measures are described in Volume II, Appendix D of this report.

Multiple grout alternatives were considered in the study. These alternatives reflect different locations of deployment on the site, different on-site disposal forms (containerized or monoliths), leveraging close-location off-site commercial facility grouting capabilities, and commercial disposal sites. Whether on-site grouting alternatives are performed by the tank farms contractor or a vendor is not distinguished in the selection.

Getters

Grout alternatives for immobilization of treated LAW can benefit from addition of selective "getters" that improve sequestration of specific contaminants. Although BFS acts by chemical reduction to sequester many contaminants, such as regulated metals and technetium, the material is a bulk grout-forming additive and is not usually referred to as a "getter". These selective getters are typically added in small amounts, along with the bulk of the grout-forming materials, to enhance retention of a specific contaminant, although there are also options to add the material as a barrier beneath the bulk waste form to hinder leaching of the contaminant to the environment. For the alternatives described in this section, getters are assumed to be needed to meet the leaching performance objectives criteria for on-site disposal of grout in containers at Hanford IDF for alternatives Grout 1–4. If other manipulations of the grout formulation are needed to reach the performance criteria or material properties, the adjustments are assumed to be included. The key contaminant of concern where getters are assumed required for on-site disposal of grouted waste forms at the Hanford IDF is ^{129}I, although getters may also be needed for the highest performing grouts to sequester ^{99}Tc (SRNL-RP-2018-00687).

The off-site and vault grout disposal alternatives are based on the assumption that getters are not needed for ^{129}I and/or ^{99}Tc, and retention of these species is reliant on the integrated disposal system. Getters could be added if shown to be needed but are not included in the cost estimates for these alternatives.

RCRA Hazardous Metals

Grouting alternatives are based on the assumption that "getters" would not be needed for RCRA hazardous metals. Because of their technical and economic effectiveness, solidification/stabilization methods, using cement and other additives either alone or in conjunction with other types of treatment such as incineration, are the recommended Best Demonstrated Available Technology (BDAT) for at least 57 RCRA-listed wastes, including metals (EB071.02W, *Solidification and Stabilization of Wastes Using Portland Cement*). Solidification/stabilization methods have been specifically designated as BDAT for Ba, Cd, Cr, Pb, Hg, Se, and Ag (based on treatment/treatment train) (EPA/530/R-93/012, *Technical Resources Document on Solidification/Stabilization and Its Application to Waste Materials*) and these could be present in tank waste above regulatory limit levels.

For mercury, solidification/stabilization has been specifically designated as the recommended BDAT for Hg (D009), with <260 mg total Hg/kg waste (55 FR 22572, "BDAT Treatment Standards for D009," and EPA/530/R-93/012). For chromium, solidification/stabilization has been specifically designated as the recommended BDAT for Cr (D007) (one alternative) (55 FR 22563, "e. Chromium," and EPA/530/R-93/012).

Regulated Organics

The acceptability of grouting alternatives assumes that the LDR organic concentrations in the final waste form meet regulatory requirements. If the concentrations of some organics in the staged, pre-treated waste exceed levels that would result in a compliant final form, then additional evaporation or low temperature oxidation would be applied or the waste is assumed to be diverted to the LAW melter for processing. Waste evaporation to both remove LDR organics and reduce waste volume are relatively mature technologies, although the effectiveness of LDR organic removal of all species is yet to be completely demonstrated.

Additional treatment that may be necessary to destroy some organics is at a low maturity level, and testing is ongoing in this area. Similar to that mentioned above for removal of strontium and plutonium, all grouting alternatives assume that the liquid waste is sampled, analyzed, and tested as necessary prior to processing to ensure pretreatment to remove ^{137}Cs and evaporation (and additional LDR organic treatment if needed) will enable meeting the waste acceptance criteria for subsequent treatment or will be staged for vitrification.

Nitrate and Nitrite

Unlike vitrification or FBSR, nitrate and nitrite are not destroyed or form NO_x vapor, nor do cement-based/slag-based grouts provide any enhanced chemical stabilization. These anions are considered "mobile" species within a grout waste form, as they are concentrated in the pore solution and have a sorption (liquid-solid partitioning coefficient) retardation factor of <1, indicating very little retention under saturated conditions. Lowered nitrate/nitrite release rates have been measured in recent testing efforts that used grout waste forms with decreased porosity (physically slowing migration of the anions); however, the technology to do this consistently at large scale is not mature. An assessment of NO_3/NO_2 release from a supplemental LAW grout inventory in the IDF showed that existing leach testing results are close to meeting maximum contaminant levels (MCL) in groundwater for nitrate release in the IDF based on existing drinking water compliance standards. Note that laboratory tests are a bounding conservative case due to the saturated nature of the tests (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3). Numerous laboratory studies and field demonstrations, including at the Hanford Site, have used the inherent denitrifying capacity of subsurface environments for in situ remediation of NO_3 and co-contaminants. Nitrate and nitrite concentrations in a grout waste form disposed of offsite is inconsequential because the disposal sites have no pathway to potable water.

Working Grout Container Inventory

For alternatives with off-site disposal of containerized grout, the working inventory of containers onsite or in transit at any point in time is estimated at a maximum of 750. This estimate is based on an average estimated production rate of 130 containers per month, with a maximum of 300 per month (10 per day). These 300 containers would not be shipped until the 28-day cure time has completed, so there is a nominal continuous inventory of 300 containers curing, plus 10 per day that have completed curing. One train per 15 days would need a maximum of 30 railcars containing 150 containers per shipment (SRNL-RP-2018-00687). Additionally, an allowance is assumed for a possible 15-day lag time for other circumstances (e.g., weather) and 15-day transit and disposal time. In the event of a suspension of shipping for transportation or disposal site interruptions, the maximum inventory onsite or in transit of grouted material awaiting disposition until the issue is resolved would be 750 containers.

Removal of ^{129}I and/or ^{99}Tc or Sample-and-Send

Removal of ^{129}I and/or ^{99}Tc are considered as augmented processes in alternatives Grout 1C and 2C, where all other flowsheet assumptions are consistent with alternatives Grout 1A and 2A, respectively.

Similarly, a "sample-and-send" approach in which the waste is sampled and analyzed for ^{129}I and/or ^{99}Tc is an augmented activity in alternatives Grout 1D and 2D. After grouting the waste, grout containers with concentrations lower than a threshold concentration of these radionuclides would be disposed of onsite, and those with concentrations higher than the threshold concentration would be disposed of offsite.

Flammable Gas

Production of gases that are flammable from radiolysis and thermolysis occurs in the tank waste; these processes are greatly reduced in the grouted waste form because of lower dose and waste temperature but are not completely eliminated. Small amounts of gases that are flammable have been observed to be released from grouted waste forms at other sites. Therefore, mitigation of the flammability concern from the release of these gases from the waste in a large, enclosed vault space must be evaluated and addressed for alternative Grout 5A but would presumably be less impactful for all other grout alternatives because the containers would be stored during the curing period in an engineered facility with ventilation. Even for a monolithic disposal of grout in a vault, these concerns have previously been addressed using safety controls and indications. Further, alternative Grout 5B, which places the cured containers in a vault, may not have this risk because the grout would be expected to release minimal vapors after curing before being emplaced in the vault, although an engineering evaluation would be needed to confirm. Monoliths in large vaults are not likely used for the other grout alternatives. Engineering evaluations would be needed to confirm safe storage and transport for all alternatives.

C.1.4 General Assumptions for the Alternatives

Defining Parameters

- No baseline technology was assumed for the treatment and immobilization of Hanford supplemental LAW. The System Plan Scenario 1B (ORP-11242), defines the facilities and infrastructure assumed available for all alternatives, regardless of the supplemental LAW treatment technology.
- Alternatives were not screened out solely on the basis of total lifecycle cost. Alternatives were screened out on the basis of affordability under benchmark funding level assumptions. At least one alternative representing each technology was fully evaluated, regardless of affordability.
- Off-site disposal facilities – WCS Waste Disposal Facility (Texas) and Energy*Solutions* Clive Disposal Facility (Utah) – do not have a pathway to potable water.
- Information from performance assessments (PA) consider the 1,000-year compliance period (per DOE O 435.1); projected post-compliance period information to 10,000 years is intended to provide information about potential long-term impacts, including peak dose and potential exceedance of standards beyond the compliance period (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site* [IDF PA]).
- The need for, method, and location of pretreatment will be evaluated by DOE on a case-by-case basis, consistent with DOE O 435.1.
- All activities related to retrieval, pretreatment, treatment, and disposal of tank waste will be performed in compliance with applicable DOE Orders and anticipated regulatory requirements, including Orders and requirements regarding safety, environmental protection, worker and community protection, contracting, treatment, transportation, and disposal.

Assumptions

- The first WTP LAW melter system continues to operate both melters for the duration of the River Protection Project (RPP) mission.
- The start date for radioactive operations for the WTP LAW melters is December 31, 2023 and December 31, 2033 for the HLW melters.

- The assessment uses the same assumptions for glass modeling as used in the System Plan (ORP-11242, Rev. 9) (2016 glass models). More advanced models are not expected to substantially impact the facility size (see explanation in Vitrification 2 [Section C.4]).
- HLW processing begins in December 2033. For the HLW Vitrification Facility to achieve full capacity, supplemental LAW treatment must be available within 12 to 36 months.
- The maximum feed rate to supplemental LAW treatment was determined to be 360,000 gal/month to allow conservative sizing of the supplemental LAW treatment facility versus the 264,000 gal/month maximum in the baseline (System Plan Scenario 1B [ORP-11242, Rev. 9]). All alternatives were, therefore, defined to be capable of a LAW supplemental treatment rate of 360 kgal/month. The alternatives are projected to process different amounts, depending on start-up schedule and availability of waste. This assumption determines facility and process requirements that factor into lifecycle costs.
- All alternatives will address permanent disposition of LAW from supplemental treatment. While the actual volume of LAW treated may vary between alternatives, no LAW will remain upon mission completion of any of the alternatives.
- Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion will be fully evaluated. Alternatives unlikely to comply with one or the other will be screened out.
- Direct-feed low-activity waste (DFLAW) processing begins in 2023. Cesium is removed using a TSCR system for the first 5 years of operation.
- After 5 years of DFLAW operations, LAW is pretreated in the TFPT system. TFPT doubles the capacity of TSCR.
  - Pretreatment is consistent with a waste incidental to reprocessing (WIR) process and reduces ^{137}Cs dose.
  - TFPT and TSCR removes ^{137}Cs to WTP equivalent (<3.18E-5 Ci/mol Na^{+}).
  - The assumed pretreatment of LAW in TFPT does not preclude treatment in the WTP Pretreatment Facility. (Note: immobilizing the liquid in other on-site locations for some alternatives [e.g., 200 West Area] would continue to use TFPT.)
  - Spent CST columns are stored onsite in interim storage, and the media is assumed vitrified in the HLW Vitrification Facility and empty columns are disposed in IDF.
- TFPT and TSCR treatment removes ^{90}Sr to Class A (<0.04 Ci/m^3) and plutonium to <100 nCi/g for most (~90%) LAW feed (non-complexant).
  - The WTP Pretreatment Facility would not be expected to remove significant amounts of soluble ^{90}Sr; therefore, most waste would be Class B if grouted. (Note: this categorization only impacts potential off-site disposal locations and therefore costs.) (Use of another process solely to remove soluble ^{90}Sr from non-complexant waste was not considered; this would add an unnecessary processing step because the waste form could be disposed as Class B waste without it.)
  - The Sr/TRU removal process for complexant wastes is performed as planned, regardless of the final waste form or disposal path for that stream.
- LAW is retrieved and staged for pretreatment in Tank AP-106 or another designated DST (except for alternatives Grout 3A/B and 4A/B). Detailed assumptions about the feed vector are provided in Volume II, Appendix B.

- LAW is sampled and analyzed/tested prior to treatment (sample-and-send) to ensure that a compliant waste form will be produced. Detailed additional laboratory methods are not known but are assumed to be accommodated in existing laboratory space. Sampling after pretreatment was assumed unnecessary.
- All alternatives include an evaporator to reach optimum Na^+ concentration prior to immobilization except for vitrification.
- All debris/solid waste is disposed of onsite in the IDF except alternatives where grout is produced offsite.
- All alternatives will include necessary transfer, storage, processing, and disposition facilities and projects.
- LAW immobilized by grouting or FBSR can be disposed of offsite provided the waste acceptance criteria for the off-site disposal locations are met.
- Enabling assumption to avoid restrictive screening of alternatives: LAW immobilized by grouting or FBSR can be disposed of onsite in the IDF. An IDF PA, considering all waste forms emplaced in the IDF, can demonstrate that contaminant and radionuclide concentrations at the point of compliance are not exceeding limits over the timeframes evaluated. This requirement can be achieved through predicting inventory partitioning, waste form performance, or inventory management. The PA, and any needed supportive technology development, will be completed before on-site disposal is initiated.
- All alternatives that include off-site shipment use U.S. Department of Transportation (DOT)-compliant shipping containers.
- Permits can be obtained in a timely fashion to meet the schedule.
- The IDF can be expanded to accommodate the needed volume of immobilized LAW; costs and risks of IDF expansion will be assessed where applicable.
- Both the volume and content of secondary waste streams will be evaluated against the selection criteria.
- Water infiltration into the IDF when the RCRA cap is in place is assumed to be the same as the 2017 IDF PA (0.5 mm/year) (RPP-RPT-59958), which could allow some leaching from waste forms prior to the assumed cap failure point at 500 years.
- Exogenous risks (e.g., earthquake, catastrophic flood, volcano) were assessed as indistinguishable across all technologies (vitrification, FBSR, and grouting) and disposal locations (Hanford IDF, WCS Waste Disposal Facility [Texas], and Energy*Solutions* Clive Disposal Facility [Utah]).

Vitrification Only Assumptions

- The assumed total operating efficiency (TOE) for vitrification systems is 50% (System Plan Scenario 1B [ORP-11242, Rev. 9]).
- Melters are replaced after 5 years of service.
- Some technical risks for supplemental LAW treatment will be reduced by lessons learned during WTP LAW melter operations, which are not currently available, and so some risks cannot be resolved at this time. Future knowledge is credited in risk evaluations for a parameter where appropriate. Current knowledge is also used where appropriate, such as estimating operating cost, melter throughput, and TOE.

Grout Only Assumptions

- If present above regulatory limits, LDR organics will be removed from LAW by evaporation (and oxidation, if needed) to beneath regulatory levels, if feasible; if LDR organics are present that cannot be treated by this process, the waste will be sent for WTP LAW vitrification. All flowsheets for grout immobilization show an evaporation and LDR treatment step for consistency, although it may not be needed for some wastes.
- A transfer path is assumed available for sending waste to either a grouting process or WTP LAW vitrification (for wastes that cannot be processed by grouting).
- The majority of LAW is assumed to initially be at 5.0 M [Na^+] and is evaporated to 8.0 M [Na^+] (380,000 gal condensate per 1 Mgal LAW) requiring ~30,000 gal of fuel oil.[6] Some LAW containing high phosphate content may be processed at lower [Na^+].
- For grout alternatives, getters for ^{129}I (and perhaps ^{99}Tc) are included in grout formulations for alternatives Grout 1A, 2A, 3A, and 4A, but are not needed and not included for any alternatives that include off-site disposal (alternatives Grout 1B, 2B 3B, 4B); on-site vault disposal (alternatives Grout 5A and 5B); sampling for ^{129}I and ^{99}Tc to determine disposal location (alternatives Grout 1D and 2D); or removal of ^{129}I and ^{99}Tc (alternatives Grout 1C and 2C).
- Removal of ^{129}I and ^{99}Tc is not required due to the use of getters for IDF disposal but will be evaluated as alternatives for on-site grout disposal (alternatives Grout 1C and 2C).
- The grout alternatives consider Cast Stone as a baseline formulation but acknowledge formulations can be derived based on performance or processing requirements.
- Alternative materials can be developed and made available in the event that slag (BFS) or FA become unavailable (e.g., due to ceasing coal plant operations).
- For off-site disposal alternatives, transport of immobilized waste will be performed by rail. Based on experience at other sites, loading containers onto rail cars is established capability and no development was assumed needed.
- Off-site grouting facilities will have adequate capacity for treatment (grouting) of LAW within 6 months of the start of HLW treatment:
  - Applies to alternatives Grout 4A, 4B, and 6 only
- The assumed TOE for grouting systems is not defined but is not rate limiting because of the expected oversized design and operating on weekdays only (comparable to SRS).
- For Grout 4A, 4B, and 6, the vendor is assumed to perform the immobilization processing, controls, and restrictions to produce a waste form identical to the Grout 1A alternative.

FBSR Only Assumptions

- The FBSR TOE is the same as vitrification (50%).

Funding Assumptions

- Projected expenditures will be compared to a benchmark annual budget but not screened out if it is exceeded.
- Cost escalation rates are 4% on capital and 2.4% on operating expenses. The discount rate is 3%. These are based on U.S. Office of Management and Budget (OMB) recommendations (GAO-21-119SP, *High-Risk Series: Dedicated Leadership Needed to Address Limited Progress in Most High-Risk Areas*; DOE G 413.3-21A, *Cost Estimating Guide*; OMB Memorandum M-21-09, "2021 Discount Rates for 0MB Circular No. A-94").

[6] #2 fuel oil at 138,500 BTU/gal (www.eia.gov); 8,092 BTU/gal to boil water; 85% efficiency; result is 14.5 gal water/gal fuel oil or 26,200 gal fuel oil/380,000 gal water evaporated, plus ~4,000 gal to heat the waste from ambient to boiling.

- An integrated pilot-scale test facility is needed for both the Vitrification and FBSR alternatives (to enable including streams generated from HLW processing and to examine pretreatment of recycle streams) and is included in the cost estimates.
- This study reflected assumptions of successful tank operations for duration equivalent to or reduced versus current System Planning estimates. The TOPSim model runs used the same modeling assumptions for Base Operations and Waste Feed Delivery as per the current Site planning status. Tank Integrity and DST operations are indeed inherent for all alternatives, but costs and impacts of these were beyond the scope of this study and are not included in the cost estimates provided in Volume II, Appendix F for these alternatives.
- Detailed cost estimating assumptions are provided in Volume II, Appendix F.

C.1.5 Alternatives Comparison

Table C-3 compares the alternatives identified by the FFRDC team.

Table C-3. Alternatives Comparison

Alternative Designation	Brief Description	Cross-site Transfer Required	Use Existing DSTs	Disposal	Container
No action	Use LAW melters only	✓	✓	Onsite	✓
Vitrification 1	Vitrification	✓	✓	Onsite	✓
Vitrification 2	Increase LAW vitrification rate	✓	✓	Onsite	✓
Vitrification 3	Near-tank vitrification	-	✓	Onsite	✓
FBSR 1A	Steam reforming	✓	✓	Onsite	✓
FBSR 1B	Steam reforming	✓	✓	Offsite	✓
FBSR 2A	Separate/modular FBSR	-	✓	Onsite	✓
FBSR 2B	Separate/modular FBSR	-	✓	Offsite	✓
Grout 1A	Single plant	✓	✓	Onsite	✓
Grout 1B	Single plant	✓	✓	Offsite	✓
Grout 2A	Separate plants 200 East-West	-	✓	Onsite	✓
Grout 2B	Separate plants 200 East-West	-	✓	Offsite	✓
Grout 3A	Individual plants (farms/tanks)	-	-	Onsite	✓
Grout 3B	Individual plants (farms/tanks)	-	-	Offsite	✓
Grout 4A	Offsite vendor	-	-	Onsite	✓
Grout 4B	Offsite vendor	-	-	Offsite	✓
Grout 5A	Onsite monolith	✓[a]	✓	Onsite	-
Grout 5B	Containers in vault	-	-	Onsite	✓
Grout 1C	Grout 1 + Tc/I removal	NA	NA	Onsite	✓
Grout 2C	Grout 2 + Tc/I removal	-	✓	Onsite	✓
Grout 1D	Grout 1 + Sample Tc/I/send offsite/onsite	✓	✓	Onsite-offsite	✓
Grout 2D	Grout 2 + Sample Tc/I/send offsite/onsite	-	✓	Onsite-offsite	✓
Grout 6	Phased offsite/onsite grout	✓	✓	Offsite-onsite	✓

[a] If vault monoliths are constructed in both Hanford 200 East and 200 West Areas, a cross-site transfer line would not be required for direct support of alternatives Grout 5A or 5B but would be needed for other purposes.

DST = double-shell tank.
FBSR = fluidized bed steam reforming.
I = iodine.
LAW = low-activity waste.
NA = not applicable.
Tc = technetium.

C.1.6 Hybrid Alternatives

In theory, any of the alternatives for supplemental LAW treatment can be combined with another, with phased implementation of one that transitions to the other or simultaneous implementation of two. If an alternative has lower capital expenditures in the early stages of implementation, there is the potential to use the additional available funds in ways that could advance the schedule and help reduce mission duration, cost, and tank degradation risks. After evaluating the alternatives against the evaluation criteria, the lower cost of all grout alternatives was found to offer the opportunity of phased implementation and early startup. This phased approach could include either early construction of on-site facilities and early startup or implementing off-site grout production by a vendor with simultaneous construction of on-site facilities in 2034–2035 as HLW operations ramp up production after scheduled startup in 2033. In both scenarios, the disposal of the grout waste form is assumed to initially be at an off-site facility, but with potential for a later transition to on-site disposal in a to-be-determined configuration. In all alternatives, the first phase is DFLAW vitrification, with hybrids applying to supplemental treatment of LAW.

This hybrid approach initially sends some low-activity liquid waste offsite for processing by commercial treatment contractors during the design and construction phases of the on-site facility for the alternative. Only the alternatives with on-site grout capital projects offered the financial opportunities to spend funds on these early off-site shipments. The Vitrification and FBSR alternatives required all of the benchmark $450 million/year to support the timely execution of capital projects, and any funds diverted from the projects for off-site shipments would delay the capital projects and/or increase the size of the project(s). Any additional funding expended on off-site grouting will delay the startup of on-site supplemental LAW treatment operations and further delay completion of the HLW mission. Therefore, only hybrid alternatives that involve grout as the final waste form were considered.

C.2 DETAILED ALTERNATIVE DESCRIPTIONS

C.2.1 Alternative: No Action

The “take no action” alternative simply means that the only LAW immobilization capacity during the Hanford tank waste mission would be the WTP LAW Vitrification Facility operating at 21 MT glass/day (per contractual design TOE of 70%). A simple analysis was performed that used the amount of LAW glass to be produced from both LAW and supplemental LAW treatment facilities in System Plan Scenario 1A (ORP-11242, Rev. 9) and the design capacity of the WTP LAW Vitrification Facility to estimate the minimum length of time to complete the RPP mission. In Scenario 1A, a total of 489,000 MT of LAW glass is produced. At the design rate of 21 MT/day, approximately 64 years would be required for the WTP LAW Vitrification Facility to produce the required amount of glass. (Note that the design life of the WTP facilities is 40 years [ORP-11242, Rev. 9].)

The waste loading of the LAW glass would likely be reduced if a separate supplemental LAW treatment facility is not processing a portion of the recycle stream from the melters in the WTP LAW Vitrification Facility. Thus, the glass soda loading for this scenario would likely be close to the 20% value determined for supplemental treatment of LAW during Scenario 1A. However, for simplicity, the total glass amount produced in Scenario 1A was not adjusted for the expected reduction in waste loading.

Therefore, if LAW treatment begins in 2023 with startup of the DFLAW process, the earliest possible mission completion date without increasing LAW immobilization capacity would be 2088 versus a completion date of 2066 in System Plan Scenario 1A (ORP-11242, Rev. 9). The minimum increase in LAW treatment length would be 22 years, which represents a 50% increase from the Scenario 1A mission length estimate. This simplistic analysis does not address the impact on HLW treatment, but the mission length extension for HLW processing is expected to be at least as long as that for LAW processing.

Selected studies of Hanford tank waste treatment, such as System Plan Scenario 1B (ORP-11242, Rev. 9), have evaluated the impact of a lower TOE on the overall Hanford RPP mission. The TOE that would be achieved by the WTP LAW Vitrification Facility is challenging to predict with a first-of-a-kind melter system. Analogous facilities have demonstrated TOEs of 40–50%. At an assumed TOE of 45%, the minimum mission length would be increased to approximately 89 years to process all LAW because the throughput of WTP LAW Vitrification Facility is reduced to 15 MT/day resulting in completion no sooner than 2113.

Given the predicted increase in the LAW treatment mission length and the expected impact on HLW processing, not providing additional LAW immobilization capacity for the Hanford RPP mission has been rejected as an alternative.

C.3 ALTERNATIVE: VITRIFICATION 1, SINGLE SUPPLEMENTAL LOW-ACTIVITY WASTE VITRIFICATION PLANT

(Note: This description is duplicated from the FFRDC NDAA17 report (SRNL-RP-2018-00687), with updates for the current evaluation.)

The Vitrification alternative considered in this assessment is shown in Figure C-2. Disposal of the glass waste is assumed to be in the IDF in stainless steel containers. This scenario is comparable to the vitrification from the previous NDAA17 report (SRNL-RP-2018-00687), but with a six melter LAW supplemental treatment facility. Because of the assumed annual $450 million benchmark budget for supplemental LAW treatment activities, this alternative does not begin radioactive operation until ~2047-2050, and meeting the HLW production mission schedule requires ~3× higher throughput than the current LAW melter facility, which corresponds to at least six LAW-sized melters. The cost for this additional melter facility increases by ~3× due to the larger facility with more melters but is then discounted by 40% compared to the LAW melter facility to account for scale-up and increased design and construction efficiency.

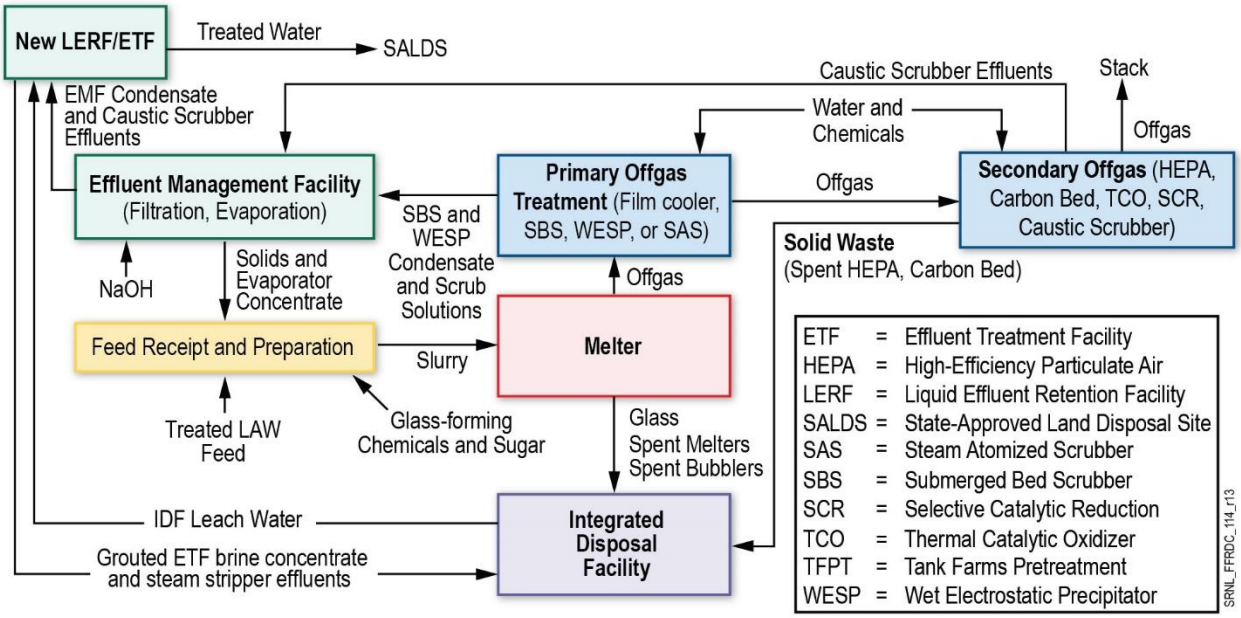


Figure C-2. Flow Diagram of Vitrification

In this alternative, the existing DST system is assumed to be used to blend and stage the feed. To transport the liquid waste to the single supplemental LAW vitrification facility, a cross-site transfer line capability would be needed, and some remote tank farms may require transfer capabilities. The waste is assumed to be sampled in the DST and analyzed and found to be compliant with the pretreatment system waste acceptance criteria to produce an acceptable glass waste form. Vitrification for supplemental treatment of the Hanford LAW is summarized below.

In the supplemental LAW melter system, the molten glass is poured into a stainless steel container to cool. Vitrification unit operations are shown in Figure C-2.

The waste components are chemically bonded as part of the glass waste form; the interaction of the waste components with the glass-forming chemicals defines the amount of waste that can be immobilized in glass. The concentration and interaction among these components define the glass properties, such as durability.

For LAW and supplemental LAW treatment, the Glass Shell v3.0 (a collection of property models) is used to constrain the composition and loading of LAW glasses to control the sulfur tolerance of the melter feed to durability response, viscosity, and refractory corrosion. The models also consider component concentration limits for chromium, halides, and phosphate. The models use the chemical composition (measured) of the waste to be vitrified. Preliminary calculations use the concentrations of sodium, potassium, and sulfur to develop a target glass composition. Then, using the property models and the 12 glass-forming chemicals identified, the target glass composition is adjusted using the glass-forming chemicals to maximize waste loading while meeting all the processing and performance constraints.

The final properties and composition of the vitrified waste form vary, but the models ensure that all the properties remain within acceptable processing and performance regions. The vitrified waste is poured using lifts into stainless steel containers. The canisters, filled to at least 90%, are cooled, sealed, and decontaminated, and are stored temporarily prior to IDF disposal.

The nitrate and nitrite salts in the LAW are converted to a mixture of nitrogen, ammonia, and NO_x in the melter by reaction with sugar, also producing carbon dioxide and other gases. The melter is continuously bubbled by forcing air through submerged pipes in the molten pool to increase the melt rate. The air and offgassed chemicals are processed through the primary and secondary offgas systems. The organic chemicals, including regulated organics, are largely destroyed by the high heat of the melter; although some other regulated organics are produced by the incomplete combustion of sugar in the melter. The sulfate in the waste has potential to form a separate phase in the melter and has limited solubility in glass. Sulfate can limit waste loading using the current glass models and can limit waste loading even with the latest glass models if accumulation in the recycle stream is higher than expected. The ammonia and NO_x are partially scrubbed into the secondary waste liquids produced in the offgas system that are processed in the Effluent Management Facility (EMF), but most passes to the secondary offgas system. The NO_x is destroyed by reaction with added ammonia in the catalytic reducer, and any remaining ammonia is released via the stack. Glass waste loading is typically 10–25% (defined as waste sodium ion loading). The waste volume is reduced versus the aqueous waste, with the glass volume equivalent to ~40–50% of the liquid feed volume.

This alternative assumes a semi-continuous process, where a specific mass of each of the 12 dry-mix components, sugar, and a volume of liquid LAW are blended and fed forward to a melter feed preparation tank in discrete batches while the melter is continuously fed from the melter feed tank. Molten glass is poured through a spout from the melter into a 564-gallon stainless steel container. Pouring into the container is done in “lifts” to avoid large changes in melt pool height. Four to five lifts are needed to fill a container. When the container is full, the pour stream is stopped, the filled container is moved, and the process repeats. The containers are allowed to cool, sealed, and swabbed for removal contamination. Any contamination is manually removed and the container is transported to the IDF for disposal.

The feed rate, bubbling rate, and melter power are balanced in an attempt to maintain a cold cap on the melt pool, other than in the immediate vicinity of the 18 bubblers. The cold cap is produced by the melter feed slurry cooling the surface of the glass. Water and other volatile components (e.g., Hg) are boiled off from the cold cap. Reactions between the nitrate/nitrite and sugar generate CO, CO_2, N_2, N_2O, NO_x, and ammonia. Small amounts of organic products from incomplete combustion of the sugar also occur primarily in the cold cap. Cold cap reactions with nitrate/nitrite and the reactions in the cold cap and plenum with oxygen result in destruction of most of the organics in the feed. Melter offgas condensate consists of components that are volatile and semi-volatile at melter temperatures. These species include Cl, F, I, Tc, Hg, As, S, and Se. In the absence of a cold cap or during operation with a reduced cold cap, these species vaporize more completely. These species are largely scrubbed out by the primary and secondary offgas processes.

All water fed to the system and the water added during offgas treatment processes becomes liquid secondary waste. The liquid secondary waste generated during vitrification is collected and processed through the EMF, which is expanded in this alternative to accommodate the additional volume from more melters. As generated, the primary waste condensate and scrubber stream is near neutral in pH. This waste is collected and processed using filtration and evaporation in the EMF. In EMF, the pH is raised to ~12, causing the ammonium in the waste stream to partition to the overheads as ammonia. The EMF evaporator bottoms are recycled to the melter for retreatment so that the radioactive and hazardous components, such as ^{99}Tc, are forced to be incorporated into the glass at higher concentrations than a single-pass system would achieve.

The EMF overhead condensate and secondary offgas system liquids are transferred to the Hanford Liquid Effluent Retention Facility/Effluent Treatment Facility (LERF/ETF) for collection and further treatment. The liquid secondary waste from the EMF evaporation process is expected to contain organics that require upgrades to the ETF treatment systems (currently in progress to treat condensate from the WTP LAW Vitrification Facility) and the volume of waste generated by a supplemental LAW vitrification process could require additional upgrades or a new facility. The liquid secondary waste from the secondary offgas system will likely contain a large fraction of the ^{129}I in the supplemental LAW feed and could require treatment prior to processing this effluent stream at LERF/ETF.[7] The volume of liquid secondary waste from the supplemental LAW treatment facility, when combined with other WTP effluents, will increase ~6× (System Plan, Section 5.1.2.4.5.5 [ORP-11242, Rev. 9]) and likely exceed the treatment capacity for the ETF. A new facility would likely be required for treatment of the supplemental LAW effluent.

After treatment in ETF, the concentrated waste from ETF is primarily ammonium sulfate; a similar process is expected if a new treatment facility is built. The waste form for the concentrated waste is currently under development, with the intent to grout the ETF concentrated waste and dispose of the waste in the IDF. Treated water from ETF is disposed of at a state-approved land disposal site (SALDS).

Solid secondary waste from the vitrification facility (e.g., high-efficiency particulate air [HEPA] filters, carbon bed media, bubblers) will be placed in a container, processed/treated as necessary to meet disposal facility waste acceptance criteria, and disposed of in the IDF or at a commercial off-site disposal facility, along with the immobilized waste from the ETF that contains the offgas condensate components from vitrification. Waste disposition will be an evolving process and efficiencies will be examined after DFLAW operations commence. Although not included as part of this alternative, disposal of the secondary solid wastes and immobilized waste from ETF concentrate in an off-site location is identified as a potential opportunity to reduce the on-site inventory of radionuclides and potential constituents of concern.

[7] Methods to mitigate the issues with iodine in the liquid secondary waste are under evaluation for WTP LAW vitrification and could be applied to a supplemental LAW vitrification system (Cree and Wagnon, 2022).

The technology parameters for the technology readiness for alternative Vitrification 1 is estimated to be moderate for this type of waste stream at this time due to previous nonradioactive simulant testing and full-scale implementation on HLW at other sites, but not in the quantities and glass production rates and waste type required for this alternative.

C.4 ALTERNATIVE: VITRIFICATION 2, INCREASED LOW-ACTIVITY WASTE VITRIFICATION RATES

The existing WTP LAW Vitrification Facility has a design basis throughput of 30 MT/day of glass and an assumed time that the facility is operating versus idled (TOE) of 70%, for an average operating capacity of 21 MT/day. If the throughput of the WTP LAW Vitrification Facility can be increased, the need for additional facilities to process LAW could be eliminated (or the capacity required for the supplemental LAW immobilization facility reduced). In addition, increasing the percentage of waste in the glass produced, or the waste loading, will reduce the amount of glass to be produced, which would lower the required production rates.

In addition, the impact of installing a third melter, changing the TOE, increasing untreated LAW lag storage to reduce the maximum processing rate needed, and breaking the recycle loop will also be considered in this alternative.

This assessment is performed using the LAW feed vector from System Plan, Run 1A (ORP-11242, Rev. 9).

Increased Waste Loading

Increasing the waste loading reduces the amount of glass generated by treating the tank waste. With the WTP LAW Vitrification Facility capacity determined by the glass production rate, increasing the waste loading allows a greater volume of waste feed to be processed each day and would reduce the need for supplemental treatment, as shown in Figure C-3. As shown in the figure, the facility glass output is constant at 640 MT/month, while the amount of sodium oxide (soda) processed is determined by the waste loading, varying from 32 MT/month at 5% soda loading to 192 MT/month at 30% soda loading. Sodium, as the dominant glass-forming species in the waste, is used as an indicator of the total amount of waste in the glass.

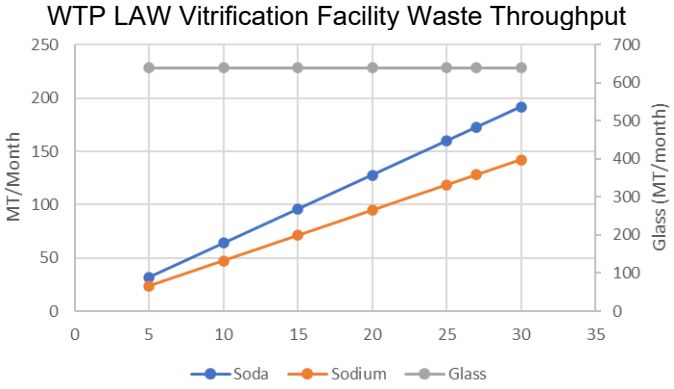


Figure C-3. Impact of Waste Loading on Waste Throughput

The glass models use the composition of the melter feed to predict a number of glass properties, such as melt viscosity and glass durability, and the solubility limits for species like chromium and sulfate that have limited solubility in the LAW glass. The glass models are used to determine both the minimum amount and type of the glass-forming chemicals to be added to each batch of feed. Improvements in the property predictions, along with formulation changes to improve solubility, have led to models (denoted by the year the final report on the model development was issued) that allow increased waste loadings for LAW processing, as shown in Table C-4.

Table C-4. Waste Loading as a Function of Glass Model

Glass Model	Expected Average Waste Loading[a]	Total Amount of LAW Glass (MT)
2007	15.6%	~800,000
2016	27.3%	489,000
2020	30.7%	420,000

[a] Waste loadings in this table are total amount of all oxides in the LAW, not soda loadings.
LAW = low-activity waste.

ORP-11242 used the 2016 glass models that resulted in average soda loadings at the WTP LAW Vitrification Facility of 23% and average waste loadings for supplemental LAW of 27.3% that result in a total glass amount of 489,000 MT. According to DOE's projections, use of the 2020 models would reduce the total amount of glass produced to 420,000 MT. Additional improvements in the LAW waste loading are expected to be small, as the most significant issues impacting waste loadings have been addressed to achieve the improvements noted in Table C-4.

WTP LAW Vitrification Facility Capacity Compared to Total Glass Production

LAW processing begins during the DFLAW program, with glass production starting in 2023. The end date of the mission varies depending on the assumptions made for HLW processing, but the ORP-11242 end date of 2066 was used in this evaluation. The WTP LAW Vitrification Facility treatment capacity during the 42-year mission is 322,000 MT of glass if the facility runs at the designed capacity. Given the total amount of glass expected exceeds this value by a significant margin, waste loading increases alone will not allow the WTP LAW Vitrification Facility to complete the mission on schedule. Thus, increased waste loading could reduce, but will not eliminate the need for supplemental LAW treatment without throughput increases in the WTP LAW Vitrification Facility.

Increased Throughput

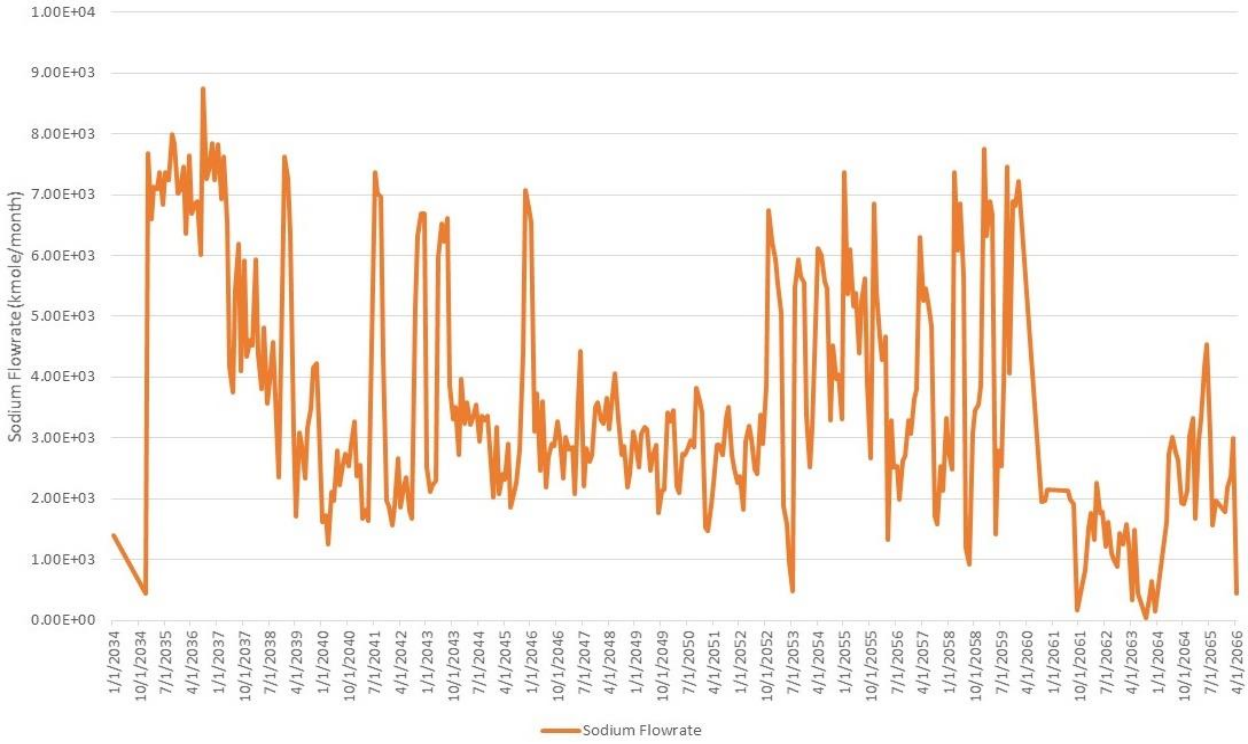
Assuming 489,500 MT of glass production is needed based on the RPP System Plan (ORP-11242, Rev. 9) (and the 2016 glass models) and a 42-year mission length, the throughput of the LAW Vitrification Facility would need to increase to an average of 31 MT/day. At the design capacity of 21 MT/day (30 MT/day capacity × 70% TOE), LAW processing would take a minimum of 64 years.

However, the total LAW processing capacity is not based on an average glass production rate since the total amount of total LAW feed each month varies considerably due to variations in HLW processing and tank waste retrievals.[8] Projected monthly feed variations result in required LAW throughput peak requirements that are much higher than the average throughput and valleys that are significantly lower, as shown in Figure C-4. Note that the chart shows sodium throughput; but if a constant waste loading is assumed, the required glass production would follow a very similar trend. At the maximum assumed monthly LAW flowrate, a LAW treatment capacity of 66 MT/day would be required. Adjusting for an assumed TOE of 70%, the required total capacity for LAW vitrification would be 94 MT/day. Increasing the soda loading has the potential to reduce this value to approximately 80 MT/day, or 40 MT/day per melter.

[8] Figure C-4 only shows the supplemental LAW treatment flowrates. Feed to the LAW treatment facility is assumed to be constant and would simply increase all values on the chart by the same amount.

Pilot-scale testing to increase the throughput of the LAW melters was documented in Hamel et al. (2006). The pilot-scale facility was able to demonstrate operation above the design basis without modifications, with some test runs achieving the equivalent of 21 MT/day/melter. The authors concluded that increasing the melter surface area by reducing the thickness of the refractory could lead to a 47% increase in throughput, and increasing the temperature to 1175°C would lead to an additional 22% increase (Hamel et al., 2006) for a potential cumulative increase of 80%. These cumulative increases, if realized, would lead to a capacity 74 MT/day for the WTP LAW Vitrification Facility or 37 MT/day per melter.

Since the 2006 study was published, DOE has further estimated that an increase in operating temperature to 1200°C could result in a production rate of 90 MT/day (45 MT/day per melter), which would eliminate the need for additional LAW treatment capacity when compared to the needed capacity requirements (81 MT/day) at 25% waste loadings. However, as discussed below, the ability of the melter to support increased capacity does not mean the other components of the WTP LAW Vitrification Facility can support the increased production rates.



Note: Flowrate from 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

Figure C-4. Sodium Flowrate to Supplemental Low-Activity Waste Treatment

Installation of a Third Melter in WTP-LAW Facility

The WTP LAW Vitrification Facility was originally designed to have three melters, and the current contract[9] for construction of the facility requires the design to allow installation of a third melter. However, design changes to the facility (e.g., the addition of unit operations to the melter offgas trains) led to use of space set aside for the third melter in the existing design. Thus, installation of a third melter is not deemed practical in the WTP LAW Vitrification Facility.

[9] WTP Contract No. DE-AC27-01RV14136, Modification No. 271, Section C states: "*The LAW Facility design shall not preclude the installation of a third melter, melter power and control systems, melter feed, offgas treatment, container handling, HVAC, and other systems and components not initially installed. The capacity to expand the waste treatment shall be consistent with an increase in the design capacity of 30 MTG/day to 45 MTG/day*."

Total Operating Efficiency Impacts

The assessments above were performed assuming a TOE of 70%, as specified by the WTP contract (DE-AC27-01RV14136). Analogous facilities have typically operated at lower TOEs, thus a lower TOE for the WTP LAW Vitrification Facility was evaluated. A lower TOE would reduce the glass production rate and require more capacity.

The evaluation of a lower TOE is not as straight-forward as simply taking the capacity at 70% (94 or 80 MT/day depending on assumed waste loading) and applying a differential factor, because the TOE for HLW vitrification should be assumed to be lower if the LAW TOE is lowered. Because the feed volumes to LAW processing are dependent on the HLW processing rate, recalculation of the entire mission is required to assess such an impact.

This recalculation was performed as System Plan Run 1B (ORP-11242, Rev. 9). In this run, the mission length extends to 2076, and the maximum required capacity for LAW processing is reduced to 54 MT/day prior to adjusting for TOE. Using a TOE of 50%, the total required LAW processing capacity is 108 MT/day (Table C-5). Improving the waste loading could decrease the required capacity to approximately 86 MT/day. Thus, the impact of a lower TOE on the overall mission results in a need to increase the total LAW processing capacity, but these increases are not directly correlated to the ratio of TOEs since HLW processes would run slower.

Table C-5. Comparison of Capacity for System Plan Model Runs 1A and 1B

Model Run[a]	TOE	Required Capacity for LAW (20% Soda Loading) (MT/day)	Required Capacity for LAW (25% Soda Loading) (MT/day)
1A	70%	94	80
1A	50%	108	86

[a] Model run data from ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

LAW = low-activity waste. TOE = total operating efficiency.

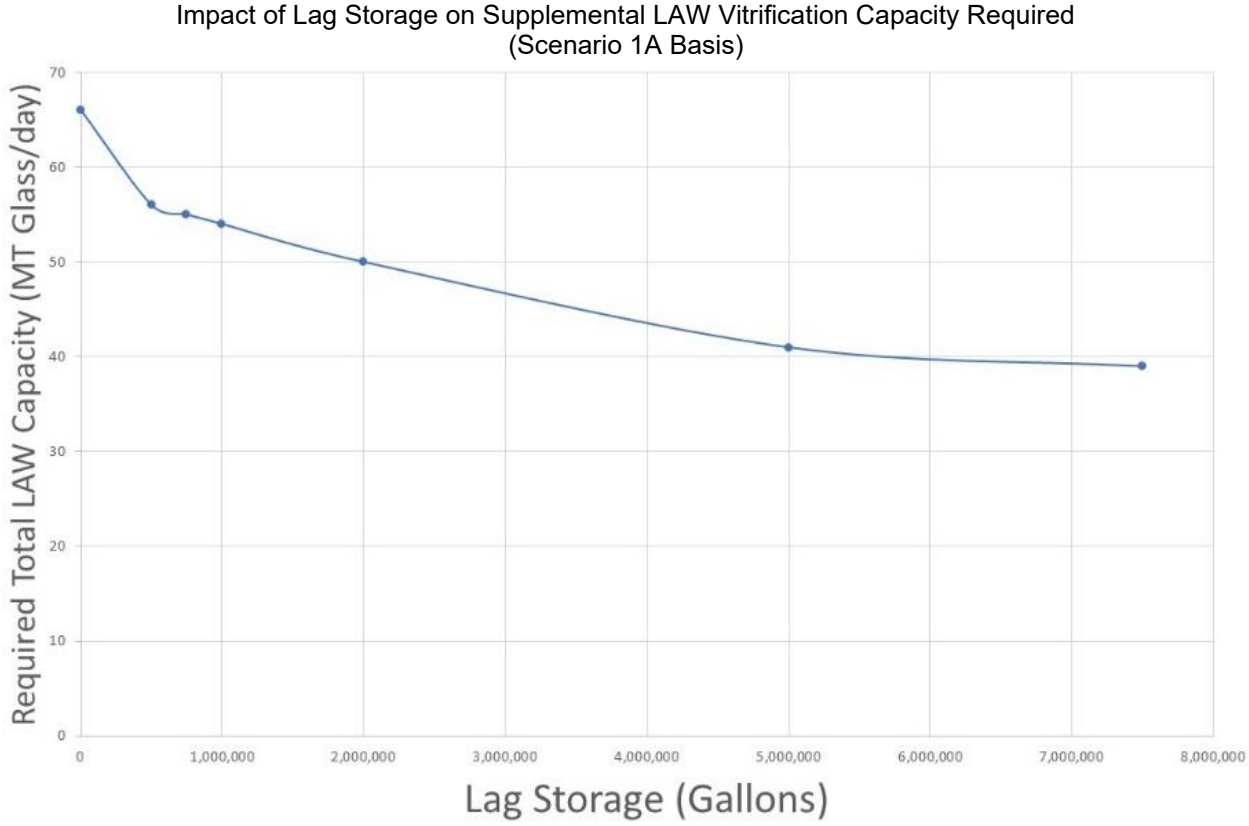
Increased Feed Lag Storage

The average capacity need for LAW treatment once HLW processing starts was estimated to be 39 MT/day (or 56 MT/day after application of a 70% TOE) for the LAW feed vector from System Plan Scenario 1A (ORP-11242, Rev. 9), approximately one-half of the maximum required production rate.[10] Lag storage can be used to even out the feed to the LAW Vitrification Facility by storing feed during periods when the feed volume exceeds the average amount and providing LAW feed when feed volumes are low. As the amount of lag storage available is increased, the required LAW immobilization capacity is decreased. Note that use of Tank AP-106 to stage LAW feed is planned during the DFLAW portion of the mission; continued use after DFLAW processing would provide approximately 1 Mgal of lag storage capacity.

An evaluation was performed of the required supplemental LAW vitrification capacity (i.e., capacity with varying amounts of available LAW feed lag storage capacity) with the results shown in Figure C-5 based on the monthly volumes in Scenario 1A. A waste loading of 20% was used for the vitrification evaluation. As shown in Figure C-5, the required capacity approaches the average as the lag storage volume approaches 6 Mgal.

[10] This average treatment need is higher than the value indicated in the increased throughput section because the simplistic analysis in that section did not account for the DFLAW portion of the mission, where the treatment rate is limited by the ability of the tank farms to provide feed.

Based on this evaluation, the required LAW treatment capacity could be reduced to a capacity close to the average capacity need of 39 MT glass/day if 6 Mgal of lag storage is provided. The required capacity is only slightly reduced to 55 MT/day by the 1 Mgal of lag storage provided by use of Tank AP-106. Thus, lag storage could be used to reduce the required amount of LAW treatment capacity needed.



Note: Based on Scenario 1A from ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

Figure C-5. Required Vitrification Rate Versus Lag Storage Amount

Breaking the Recycle Loop

One option for increasing the waste loading, and thus the waste throughput, of the WTP LAW Vitrification Facility is to eliminate recycle of the offgas condensate. Proposals to grout the evaporated offgas condensate instead of recycling would eliminate returning sulfate, chlorine, and fluorine to the melter feed; thereby potentially allowing higher waste loading.[11] However, the retention of ^{99}Tc and ^{129}I in the glass would be reduced to their single-pass retention values (38% for ^{99}Tc and likely <10% for ^{129}I) (24590-WTP-RPT-PT-02-005 *Flowsheets Bases, Assumptions, and Requirements*). These values would be even lower if the melt pool temperature is increased.

[11] The impact of the recycle stream is reduced as glass models and LAW formulations continue to improve; therefore, the impact of breaking the recycle loop is lessened with these models. For the 2016 models, the difference in WTP LAW Vitrification Facility versus supplemental LAW soda loadings (23% vs 20%, respectively) provides insight into the amount of impact from the recycle stream since the supplemental LAW processes a higher amount of recycle than the WTP LAW Vitrification Facility.

Processes have been tested to separate ^{99}Tc from the recycle to allow preferential return of only the ^{99}Tc, but these processes (documented in the following) would not address iodine retention.

- SRNL-STI-2019-00006, *Solid-Liquid Separation Testing for the Remediation of Hanford Waste Treatment Plant Low Activity Waste Melter Off-Gas Condensate; SRNL-STI-2018-00047, Evaluation of Immobilizing Secondary Waste from a Proposed Treatment Process for Hanford WTP LAW Melter Condensate*
- SRNL-STI-2017-00322, *Bench Scale Experiments for the Remediation of Hanford Waste Treatment Plant Low Activity Waste Melter Off-Gas Condensate*
- SRNL-STI-2017-00087, *Investigation of Variable Compositions on the Removal of Technetium from Hanford Waste Treatment Plant Low Activity Waste Melter Off-Gas Condensate Simulant)*.

Development of these processes could allow breaking the recycle loop to be a more viable option.

Without a process to remove the ^{99}Tc and ^{129}I from the offgas condensate, most of the ^{99}Tc and ^{129}I would be partitioned to a secondary waste that is assumed to be grouted, and the efficacy of operation of the WTP LAW Vitrification Facility could be questioned – What is the incremental benefit gained by incorporating a small fraction of the ^{99}Tc and ^{129}I in glass if the majority ends up in grout? In other words, if grouting the recycle stream is deemed acceptable, why not simply grout the tank waste? Operation of the vitrification facility to achieve destruction of organics and nitrate in the waste appears to be a highly inefficient use of resources.

Other Considerations

Impact on WTP LAW Vitrification Facility if Supplemental LAW Treatment is Eliminated

The WTP LAW vitrification process recycles the melter primary offgas condensate back to the melter feed tanks after evaporation to remove water. When supplemental LAW treatment is operational, a portion of the recycle stream from the WTP LAW Vitrification Facility is sent to the supplemental LAW treatment facility. All recycle streams in supplemental LAW are handled internal to the process. As a result, the WTP LAW Vitrification Facility can operate at a higher soda loading than supplemental LAW processing (23 versus 20%, respectively for System Plan Scenario 1A [ORP-11242, Rev. 9]). If significantly increased throughput at the WTP LAW Vitrification Facility is achieved that allows the elimination of the supplemental LAW treatment facility, all LAW vitrification recycle streams would be handled internal to the WTP LAW Vitrification Facility. Thus, the achievable waste loadings in LAW vitrification could be reduced by the recycle stream. The size of this impact would need to be demonstrated based on the glass models to be used during processing.

Impact of Increased Throughput on Process and Support Systems

The melter is only one part of the WTP LAW Vitrification Facility. Operation of the melter at increased rates would require all process and support systems to keep pace with the melter. Many of these systems are designed with very little margin for increasing facility throughput.[12] Past evaluations of the ability of the WTP LAW Vitrification Facility to process at higher rates did not include the impact of higher waste loadings, which impacts the cycle times of the melter feed and condensate tanks, among other impacts.

[12] Exceptions are the Glass Formers Reagent System and Analytical Laboratory: Contract language for these facilities include the requirement to support LAW operations at 45 MT/day for the glass-former feed at 45 MT/day and analytical laboratory capabilities are required to be designed to support an increase in LAW treatment capacity that includes supplement LAW treatment operations.

Operation at 3× the current capacity is likely not supportable for the support systems, such as the melter feed preparation process, the offgas systems, cooling water systems, offgas condensate collection systems, melter power supplies, canister lidding, decontamination, and handling. An engineering evaluation of the full WTP LAW Vitrification Facility and support functions (e.g., the WTP Analytical Laboratory and EMF) would be needed to assess the amount of maximum likely throughput each system could support.

As an example of this impact on WTP LAW vitrification operations, the cycle times of the melter feed preparation vessel were calculated. At the current 15 MT/day/melter rate, each melter feed preparation vessel would cycle 1.5 times per day or once every 16 hours, assuming 8 M sodium feed and 25% soda loading. At the lower molarities expected during DFLAW processing, necessary cycle times would be reduced to 12 hours per cycle. Operation at 45 MT/day/melter would reduce the necessary cycle time for the melter feed process to 5 hours at 8 M and 4 hours at 5.5 M. These cycle times are likely not achievable based on the transfer times at the current pump rates and the time needed to batch and transfer the glass-forming chemicals.

Reducing the required rates using lag storage could reduce the required rate to 39 MT glass/day, which is likely a more achievable target; although it is not certain that the WTP LAW Vitrification Facility and support facilities could support operation at this rate at high waste loadings.

Impact of Increased Melt Pool Temperature

Increasing the melt pool temperature would have a number of impacts on the process, including reducing the design life of the melter and melter components like the bubblers; however, the primary concern for this evaluation is the impact on retention of semi-volatiles in the melter. Retention of all semi-volatile species would be decreased, but the impact of reduced retention of sulfate, chlorine, and fluorine would be most impactful for melter operations. Given the expectation of higher amounts of these species in the offgas condensate recycle, the allowable waste loadings would be reduced. Like other impacts, process modeling will need to be conducted to assess the impact. However, the single-pass retention of species at the higher operating temperature would need to be estimated for the higher operating temperatures prior to performing the model run.

Expected melter decontamination factors (DF) would be reduced for ^{99}Tc and ^{129}I, and for ^{137}Cs and other semi-volatile compounds. Like sulfur, chlorine and fluorine, revised DFs would be needed, and the impacts assessed.

Impact of Turndown

The LAW melters, as currently designed, have a limited ability to operate at lower rates than the design capacity. When the melters are operated at decreased rates, the cold cap coverage is not sufficient to prevent higher losses of volatile species. Thus, operating a vitrification system with a feed stream that has the variability projected for the total LAW feed amount presents problems with either operating at below design capacity and/or frequently idling the melter processes. Installation of additional lag storage would alleviate this issue. However, if additional lag storage is not provided, the impact of idling or lower feed rates on the DFs of semi-volatiles species must be evaluated.

Impact of WTP LAW Vitrification Facility Modifications

The WTP LAW Vitrification Facility is assumed to begin operations with the current design. Thus, any modifications, even if minor, would require the existing process to stop operations for some length of time. If the modifications are minor and could be coordinated with a melter changeout, this impact could be small. The modifications would be performed to a facility that has been contaminated from the initial operations, which could add cost and schedule to the modification process. The amount of outage time and scope of the required modifications would need to be assessed to determine the impact of the outage on the overall mission and the estimated costs.

Overall Conclusions

This evaluation showed that improvements in the melter unit operations (increases in soda loading coupled with increased throughput) may be capable of achieving the throughput necessary to treat all of the LAW generated, at a rate sufficient to meet the projected 42-year mission length. However, it is not clear what the maximum rate that could be supported by the other unit operations in the WTP LAW vitrification processes nor whether other support facilities would allow operation of the WTP LAW Vitrification Facility at higher capacity.

Due to variability in the feed delivery rate required to maintain an integrated tank retrieval and treatment mission, the required treatment capacity is roughly a 3× increase (to a least 90 MT/day and as high as 108 MT/day assuming 70% TOE) compared to the existing WTP LAW Vitrification Facility capacity. The 3× capacity increase is not likely to be achieved without significant redesign and expansion of the existing LAW vitrification facility. Lag storage of LAW feed can be used to level out the variability in the LAW feed rate. An analysis of the required lag storage capacity required suggests that roughly 6 Mgal would be required to reduce the 3× capacity spikes to the average capacity required (~56 MT/day assuming 70% TOE) without impacting the HLW mission duration.

With the information currently available, the capacity to increase throughput of the WTP LAW Vitrification Facility cannot be determined. Previous studies of throughput increases did not adequately account for the impacts of waste loading on melter feed system and offgas condensate handling systems. Additional evaluations of the WTP LAW Vitrification Facility to assess the capacity of the facility to increase production given the current assumed waste loadings and feed sodium concentrations are beyond the scope of this study. If pursued, such a study would benefit from operational experience gained during startup, commissioning, and initial operation of the WTP-LAW Vitrification Facility. Therefore, this option was not scored during this evaluation.

C.5 ALTERNATIVE: VITRIFICATION 3, NEAR-TANK VITRIFICATION

Alternative Vitrification 3 uses multiple, off-site fabricated transportable vitrification units to treat supernatant liquid at separate plants in each for the 200 East and West Areas, or several plants associated with tank farm groupings. The immobilized glass waste form would be disposed onsite. The main intent of this alternative is to reduce the cross-site transport of untreated waste and to provide flexibility in retrieving and processing 200 West Area waste.

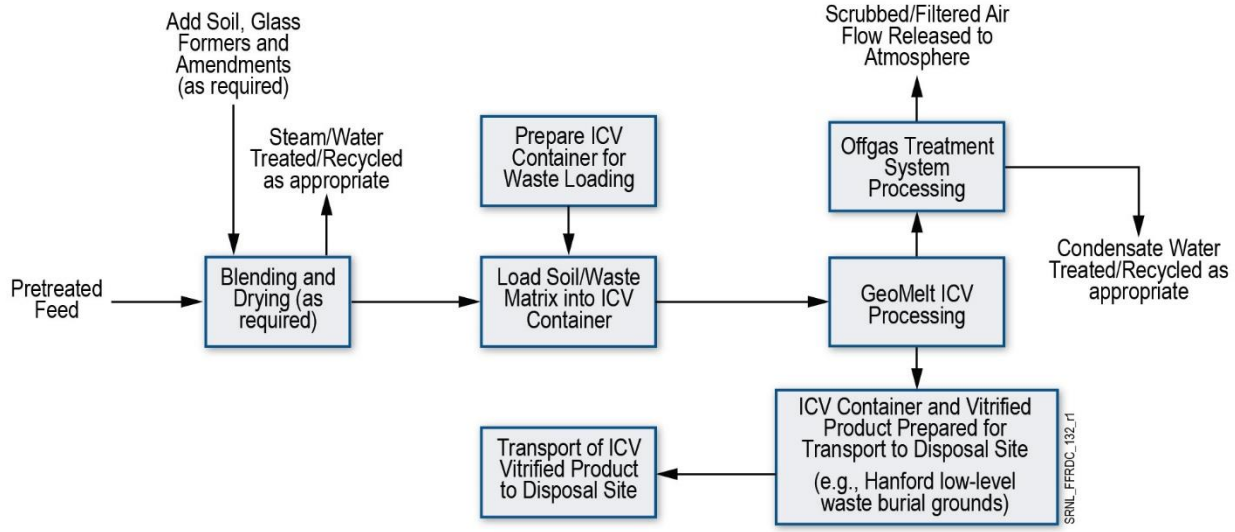
Near-tank vitrification converts radioactive liquid waste to a durable borosilicate glass waste form with properties similar to the LAW glass produced in the WTP LAW Vitrification Facility and alternatives Vitrification 1 and Vitrification 2. The technology can be deployed remotely and moved to the waste stream to be treated (e.g., 200 West Area, 200 East Area B complex, or near WTP). Near-tank vitrification can be realized in multiple configurations, including GeoMelt® In-Container Vitrification™ (ICV) (Raymond et al., 2004), Transportable Vitrification System (TVS) (Whitehouse et al., 1995), and Dem&Melt (Didierlaurent et al., 2019a) as examples. All three commercial systems are well developed and demonstrated at least to pilot scale. The TVS was used for treatment of Oak Ridge National Laboratory mixed waste sludges (Zamecnik et al., 1998). The Dem&Melt has been tested at pilot-scale with decommissioning and dismantling wastes from French nuclear reprocessing facilities (Didierlaurent et al., 2019a) and Fukushima secondary wastes (Didierlaurent et al., 2020; Didierlaurent et al., 2019b). The ICV was designed and demonstrated at full scale with Hanford LAW simulant (30686-RT-0003, *Demonstration Bulk Vitrification System Series 38 Full-Scale Testing*; Witwer et al., 2008) and demonstrated twice in pilot-scale test melts with actual Hanford tank waste (Bagaasen et al., 2004). ICV has also been deployed for treatment of a variety of wastes worldwide, including DOE Office of Environmental Management (EM) wastes at INL (Walling et al., 2021; Finucane et al., 2020; Finucane and Campbell, 2006; Witwer et al., 2013; Garrett et al., 2020).

The ICV configuration was selected as the reference near-tank vitrification technology for alternative Vitrification 3 due to the abundance of design and operating data specific to Hanford supplemental LAW generated through the Demonstration of Bulk Vitrification System (DBVS) program (RPP-24544, *Demonstration Bulk Vitrification System Independent Qualified Registered Professional Engineer (IQRPE) & RCRA Review Package*; RPP-RPT-35775, *Process Hazard and Operational Analysis for the Demonstration Bulk Vitrification System in Support of Critical Decision 3*).

Consistent with other vitrification alternatives, the waste is assumed to be blended, staged, and sampled in a DST and analyzed and found to be compliant with the pretreatment system such that the feed would produce an acceptable waste form after treatment. The tank waste would be pretreated through TFPT units and collected in a lag tank to await vitrification processing (DSTs such as Tank AP-106 in 200 East Area will be used to provide 1 Mgal of lag storage, or a ~100,000-gallon lag storage tank is expected to be sufficient).

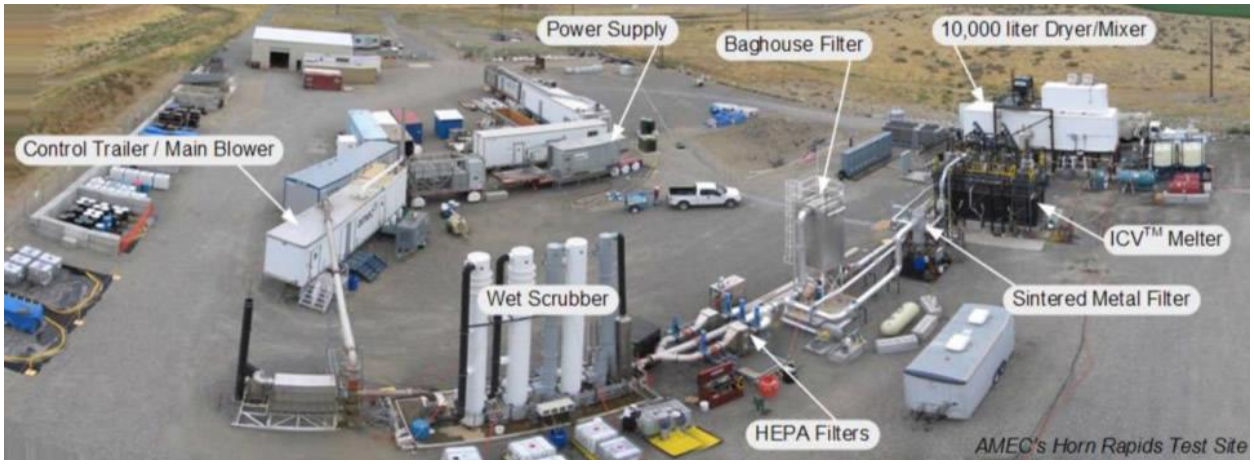
Near-Tank Vitrification Technology

Near-tank vitrification as designed and demonstrated for application to supplemental treatment of LAW is based on ICV, as shown in Figure C-6 and Figure C-7. The pretreated LAW is blended with glass-forming chemicals in a concentrator/dryer operated at 60°C at a vacuum of 26 in Hg. The dryer offgas system consists of a particulate filter and a liquid condenser. The filter is regularly backpulsed and the particulate recycled. The dryer offgas is combined with the melter offgas stream for further treatment. Condensate secondary waste is collected and transported to LERF/ETF to be treated and discharged, while HEPA filters are drummed and disposed. The melter feed is dried to roughly 5 wt% H_2O and fed into a melter through a dry waste transfer system (DWTS). The melter is a 24 × 7.5 × 7.5-foot steel box. The melter is prestaged with refractory walls, a melt starter path, electrodes, and lid. The lid is connected to both the DWTS and melter offgas treatment system.



Source: 30686-RT-0003, 2007, *Demonstration Bulk Vitrification System Series 38 Full-Scale Testing*, AMEC Nuclear, Ltd., Richland, Washington.

Figure C-6. Process Flow Diagram for Demonstration Bulk Vitrification System



Source: Witwer, K.S., E.J. Dysland, J.S. Garfield, T.H. Beck, J. Matyas, L.M. Bagaasen, S.K. Cooley, E.M. Pierce, D.S. Kim, and M.J. Schweiger, 2008, "Hanford's Supplemental Treatment Project: Full-Scale Integrated Testing of in-Container-Vitrification and a 10,000-Liter Dryer," *Waste Management 2008*, WMSymposia, Inc., Phoenix, Arizona.

Figure C-7. Full-Scale In-Container Vitrification Demonstration System in Process of Vitrifying Waste

A melt is initiated by passing current between graphite electrodes through the resistive starter path, which heats the surrounding melter feed forming a continuous melt phase. As the melt phase grows, it is Joule-heated. Dried feed is added through the DWTS to maintain a cold-cap over the melt, which insulates the melt and reduces volatility (Figure C-8). The feeding and melting continue until approximately 45 t of waste glass are produced, then a top-off frit is added to reduce volatility until all of the waste is incorporated into the glass melt.

Source: 30686-RT-0003, *Demonstration Bulk Vitrification System Series 38 Full-Scale Testing*, and RPP-48703, *Bulk Vitrification Technology for the Treatment and Immobilization of Low-Activity Waste*

Figure C-8. Thermal Image of Melter Feed Piles, Cold-Cap, and Electrode in Full-Scale ICV Melt

At that point, the power is turned off and a disposal lid is placed on the box, which is subsequently rolled off to a cooling station where the melt solidifies into a solid glass waste form (Figure C-9). Unlike the joule-heated ceramic melters used in WTP where glass is poured into disposal canisters, the ICV melter box also serves as the disposal container. The glass box is then transported to IDF for disposal.

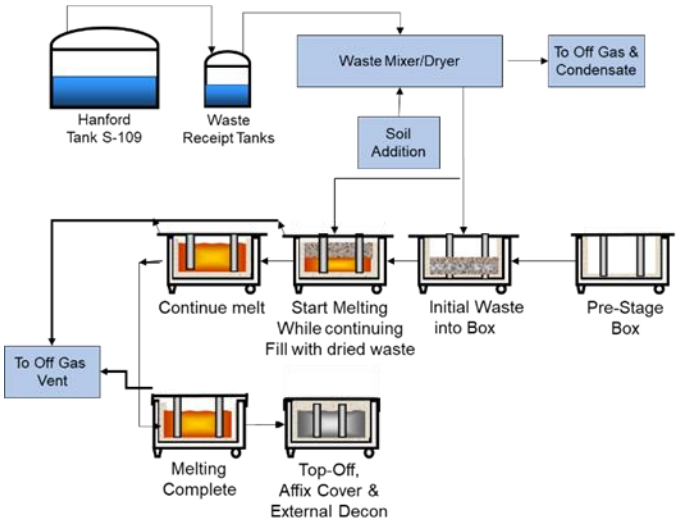


Figure C-9. Simplified Demonstration Bulk Vitrification System Flowsheet

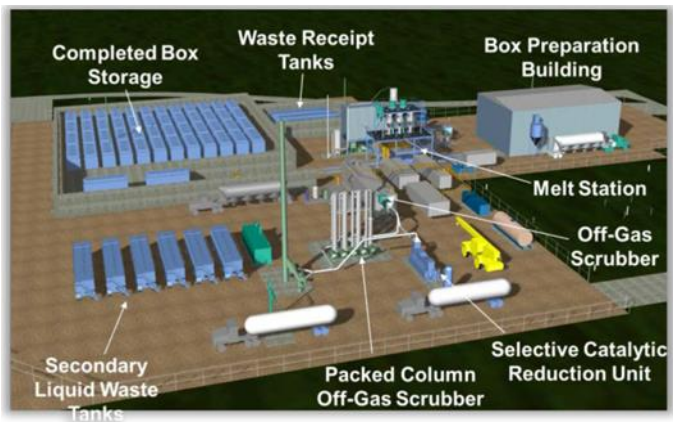
The glass composition is designed to efficiently immobilize LAW into a borosilicate glass that satisfies the current LAW glass durability criteria of normalized product consistency test response below 2 g m^{-2} and vapor hydration test responses below 50 g $m^{-2} \cdot d^{-1}$. TCLP responses were sufficient to satisfy the LDRs. Due to the higher melting temperature of the ICV process (1200 – 1350°C) and short refractory life requirements, the loading of LAW in glass can be significantly higher for similar chemical durability and can be specifically tailored for each melt (PNNL-14351, *Development and Testing of ICV Glasses for Hanford LAW*; PNNL-15126, *Laboratory Testing of Bulk Vitrified Low-Activity Waste Forms to Support the 2005 Integrated Disposal Facility Performance Assessment*). Initial melts found a small (~3%) fraction of unincorporated technetium in the box in the form of undissolved molten salt (30686-RT-0003; Bagaasen et al., 2004). This resulted in a projected fast initial, but acceptable, release in the risk assessment calculations (RPP-17675, *Risk Assessment Supporting the Decision on the Initial Selection of Supplemental ILAW Technologies*). Recent advances in glass formulation for high sulfate wastes will enable the reduction of molten salt (Vienna et al., 2014; Skidmore et al., 2019; Jin et al., 2022). A series of engineering-scaled melts with Fukushima secondary wastes have demonstrated that the solution to molten salt has been resolved by processing glass with over 2 wt% SO_3 without generating a separated salt phase (Finucane et al., 2020).

The offgas treatment system was designed to filter, scrub, and chemically treat the ICV process, dryer, and storage vessel offgases (Wilson et al., 2008). The ICV offgas is filtered with a HEPA-rated sintered metal filter, which removes and recycles 99.97% of particulate above 0.3 µm. The dryer offgas is condensed and filtered. Filtered gases from the ICV process are combined with the filtered dryer gases in a secondary treatment system. A thermal oxidizer/reducer is used to destroy organics and nitrogen oxides. Gases exiting the thermal oxidizer/reducer are quenched in an ejector venturi scrubber operated with hydroxide solution, followed by a heated HEPA filter and carbon bed and through an exhaust stack.

Technical Maturity

The ICV system to treat a complete low-curie waste tank at the Hanford 200 West Area (Tank S-109) was designed and demonstrated at full-scale (30686-RT-0003). Full design review and hazard evaluations were conducted (RPP-24544; RPP-RPT-35775). This system completed Critical Decision 3 (CD-3) and was approved to operate under a research, development, and demonstration (RD&D) permit issued by the Washington State Department of Ecology (WA 7890008967, "Permit for Dangerous and or Mixed Waste Research, Development, and Demonstration"). Construction of the system began, but was terminated due to a delay in WTP startup and contractor changes at Hanford. A detailed cost estimate was performed by an independent contractor for both the 50-box Tank S-109 demonstration (DBVS) and for a complete system to be operated in the 200 West Area and the northern portion of the 200 East Area to treat a total of 26,000 t of sodium in 4,561 boxes (ORP-11242, Rev. 3A).

Each of the 200 East and West ICV systems were projected to have up to four replicate melter lines to meet the throughput necessary for supplemental LAW treatment. A rigorous external technical review was performed to evaluate the likelihood of success of this near-tank vitrification option, which concluded: "*No fatal flaws (issues that would jeopardize the overall DBVS mission that cannot be mitigated) were found, given the current state of the project*" (RPP-31314, *A Comprehensive Technical Review of the Demonstration Bulk Vitrification System*).



Source: RPP-48703, 2011, *Bulk Vitrification Technology for the Treatment and Immobilization of Low-Activity Waste*, Washington River Protection Solutions, LLC, Richland, Washington.

Figure C-10. Rendition of Full-scale Hanford LAW Supplemental Treatment Deployment

Figure C-10 gives a rendition of the full-scale supplemental LAW version of the ICV process. A similar ICV system treating hazardous waste has been in full-scale operations in Iga-City Japan since 2001 (Figure C-11). The technology readiness level (TRL) was sufficient to satisfy CD-3 requirements (RPP-24544), with a technology maturation plan to obtain to TRL 9 was to be completed during DBVS.

Source: RPP-48703, 2011, *Bulk Vitrification Technology for the Treatment and Immobilization of Low-Activity Waste*, Washington River Protection Solutions, LLC, Richland, Washington.

Figure C-11. Iga-City In-Container Vitrification System

Although there are potential cost savings associated with the off-site fabricated/on-site assembled ICV system versus a site-built facility, each processing location would require significant site preparation, storage and processing pads, utilities, and preparation facilities. In addition, replicate melter-lines would be required to reach the throughput comparable to alternative Vitrification 1, with similar offgas treatment complexity. The advantage of avoiding use of a cross-site supernatant liquid transfer line specifically for this process by using modular/separate vitrification plants must be compared to the need for two facilities. Further, the added expense of a second facility may further extend the schedule, delaying startup and completion of the mission. Because of the cost of multiple ICV facilities with similar complexity and capacity as alternative Vitrification 1, this alternative is considered bounded by the analysis of Vitrification 1. Further consideration of alternative Vitrification 3 is, therefore, unnecessary.

C.6 ALTERNATIVE: FBSR 1A AND FBSR 1B, FLUIDIZED BED STEAM REFORMING ON-SITE (A) AND OFF-SITE (B) DISPOSAL

Note: The description below was adapted from SRNL-RP-2018-00687 for steam reforming applied to Hanford LAW with edits to provide more up-to-date input.

Steam Reforming

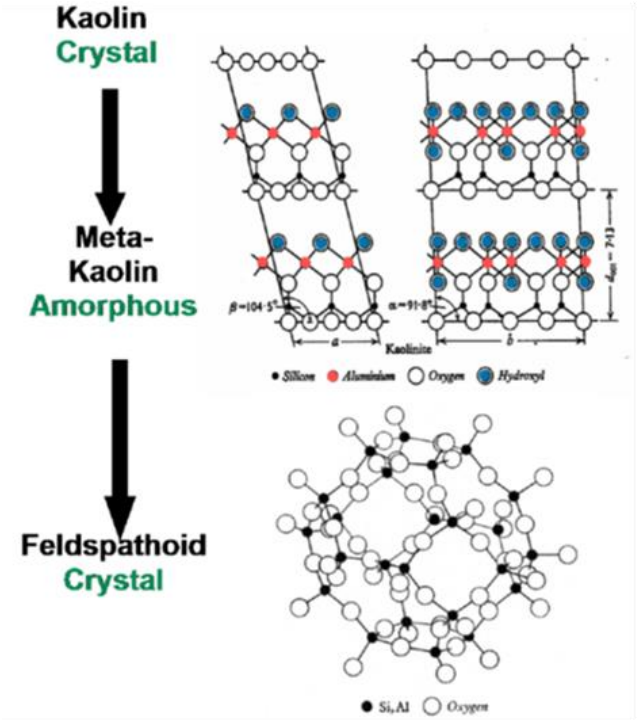
FBSR converts radioactive liquid waste mixed with a clay additive into dry granular mineral particles with chemical structures that are expected to retain the radionuclides. FBSR has been researched, developed, and used commercially for over two decades for processing low-level radioactive wastes. FBSR for supplemental treatment of Hanford LAW is summarized below.

Fluidized Bed Steam Reforming Technology

FBSR is a high temperature process that operates at temperatures up to 725–750°C to evaporate water in the waste, destroy organics, destroy nitrates, and convert the solid residue into a durable, leach-resistant waste form. For the concept of supplemental treatment of Hanford LAW, this process occurs in the DMR vessel, which contains a bed of particles that are the right size and density to be continually fluidized by steam that flows upward through the bed. The steam is superheated to nominally 500–600°C prior to entering the DMR. Coal and oxygen are fed into the DMR, where they react (also with steam) under stoichiometrically reducing (pyrolysis) conditions to heat the DMR to the target operating temperature and to produce hydrogen and other reduced gas species that react with the nitrates and nitrites in the waste feed, converting the nitrates and nitrites predominantly to nitrogen and water. Organics in the feed are efficiently pyrolyzed; nitrates in the feed are destroyed to near or below detectable levels in the mineralized waste form. Overall, up to 97% NO_x destruction was obtained in pilot-scale Hanford LAW FBSR testing (RT-21-002, *Report for Treating Hanford LAW and WTP SW Simulants: Pilot Plant Mineralizing Flowsheet*). Over 99% NO_x destruction was measured in pilot-scale INL sodium-bearing waste testing (28266-RT-001, *Pilot Plant Report for Treating SBW Simulants, Mineralizing Flowsheet*), and >90% NO_X destruction was measured in INL IWTU startup testing (RPT-1642, *Integrated Waste Treatment Unit Engineering Data Analysis of TI-102 – Part 4*). IWTU startup testing (RPT-1642) indicates that NO_x offgas concentrations could exceed the desired performance level of 1,500 ppmv (dry basis). If that translated to the FBSR for LAW, it presumably would result in additional controls being required.

The remaining dissolved and undissolved components of the supplemental LAW (e.g., sodium, aluminum, halogens, sulfur, hazardous metals, and radionuclides, if present) react with the clay that is premixed with the waste feed to form the desired mineralized waste form. This product includes highly durable minerals nepheline, carnegieite, sodalite, and/or nosean. These structures can incorporate the nonvolatile and semi-volatile elements in the waste feed either into the nepheline or carnegieite mineral structures or inside sodalite or nosean "cages" of suitable sizes to contain halogens and radionuclides (Figure C-12) (SRNL-STI-2011-00387, *Fluidized Bed Steam Reformed Mineral Wasteform Performance Testing to Support Hanford Supplemental Low Activity Waste Immobilization Technology Selection*). The relative proportions of these minerals in the waste form depend largely on the amounts of halides, sulfur, and radionuclides relative to the amounts of total sodium and potassium in the LAW.

Modeling predictions for representative supplemental LAW compositions suggest that the granular mineral product could nominally contain mostly (60–80 wt%) nepheline or carnegieite, 5–10 wt% sodalite, 6-12 wt% nosean (where sodalite and nosean could form a solid solution), and 1–10 wt% silica (SiO_2) and alumina (Al_2O_3). The relatively small amounts of sodalite and nosean minerals compared to the larger amounts of nepheline and carnegieite minerals in the mineral assemblage prediction result from the relatively small amounts of anions and radionuclides (ranging from about 3–14 mol% of the sodium) and sulfur (ranging from about 0.4–1 mol% of the sodium) in the supplemental LAW feed vector.



Resultant Nepheline – Kalsilite structures that can contain radionuclides:	
$Na_xAl_ySi_zO_4$	Group 1, 2, and certain other elements
$CsAlSiO_4$	
$RbAlSiO_4$	
$(Ca_{0.5},Sr_{0.5})AlSiO_4$	
$(Sr,Ba)Al_2O_4$	
$(Na,Ca_{0.5})YSiO_4$	
$(Na,K)LaSiO_4$	
$(Na,K,Ca_{0.5})NdSiO_4$	

Anions that can be incorporated into cages:		
Anion	Mineral Name	Oxidation State
F^-	F-sodalite	-1
Cl-	Cl-sodalite	-1
ClO_4^-	Cl-sodalite	-1
SO_4^{2-}	Nosean	+6
TcO_4^-	Tc-sodalite	+7
ReO_4^-	Re-sodalite	+7
I^-	I-sodalite	-1
Br^-	Br-sodalite	-1

Figure C-12. Sodalite "Cage" Contains Halogens and Radionuclides

Fluidized Bed Steam Reforming Alternatives for Supplemental Treatment of Hanford Low-Activity Waste

Two main FBSR cases were analyzed. Both produce a durable, mineralized primary waste form for storage and permanent disposal. The differences between the two alternatives are the disposal sites—IDF on the Hanford Site (alternative FBSR 1A) and offsite (alternative FBSR 1B)—and the FBSR processing steps needed to meet the requirements of those disposal facilities.

In both FBSR cases, two process systems in parallel receive waste from a single feed system to provide the throughput and ability to vary the throughput needed to maintain the supplemental LAW feed vector throughput.

Alternative FBSR 1A (Figure C-13) produces a monolithic primary waste form for storage and permanent disposal in the IDF on the Hanford Site. Secondary wastes also are disposed of at IDF. A geopolymer process downstream of the FBSR converts the granular FBSR product to a monolith, which is needed to meet the IDF 85 lb/in.^{2} compressive strength limit required for IDF disposal. That step is shown as part of product packaging in Figure C-13.

Alternative FBSR 1B produces a solid granular primary waste form for storage and permanent disposal offsite. Secondary wastes are assumed disposed of onsite in IDF. Off-site disposal is assumed to not require a monolithic waste form, so the geopolymer monolith production system is eliminated, making the alternative FBSR 1B process simpler. These two cases bound the potential disposal alternatives considered in this alternative.

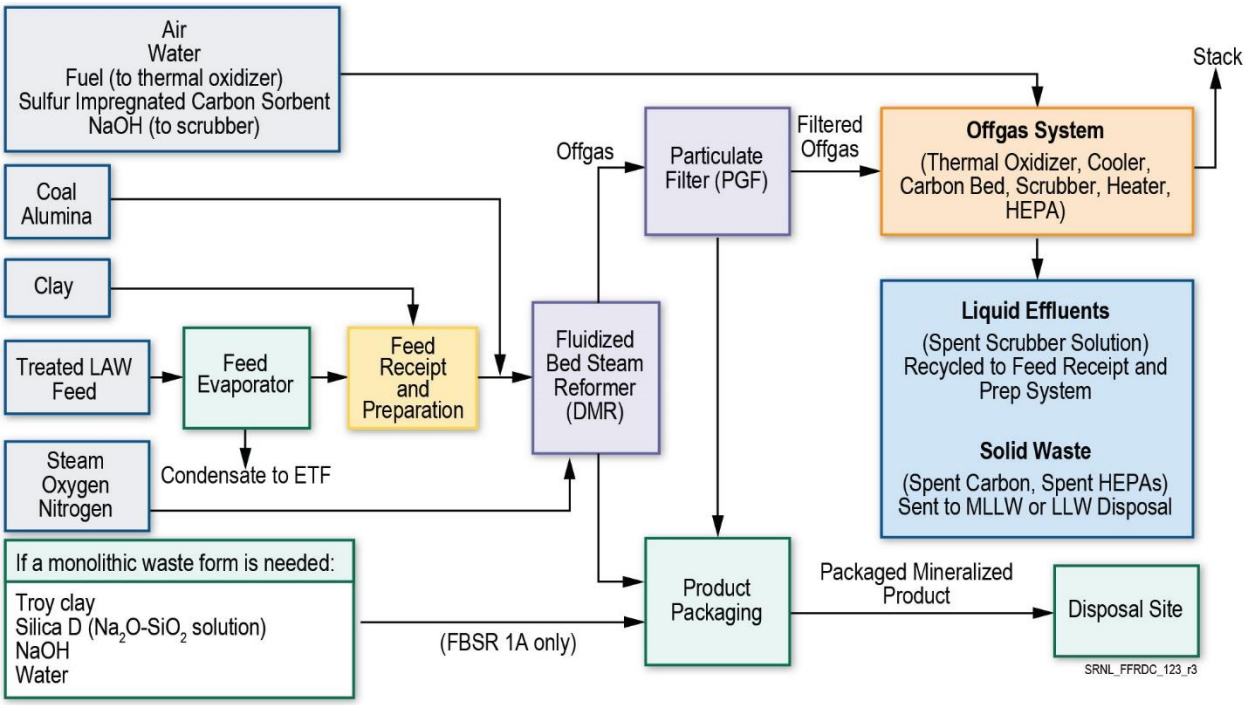


Figure C-13. Flow Diagram of FBSR 1A and 1B

In all steam reforming cases, the wet scrubber solution is entirely recycled back to the waste feed. This recycle creates a "flywheel" of the more volatile isotopes such as ^{99}Tc and ^{129}I, but the flywheel enables highly efficient capture of these isotopes in the mineralized product because the single pass capture of these isotopes is relatively high. In laboratory testing in single-pass tests without recycling, results indicate that 0-31% of the I and 13-20% of the Tc may enter the offgas with 69-98% of the recovered I and 88-98% of the recovered Tc retained in the granular product (SRNL-STI-2011-00387). The FBSR offgas system unit would require an effective scrubber to capture Tc; a caustic scrubber is BDAT for iodine for pH >12. Small fractions of these isotopes are captured in two secondary wastes—spent carbon (used for Hg control) and spent HEPA filters. The mass balance estimates and flywheel discussion are summarized in Section 1.3. Since 100% of the spent scrub solution is recycled, there is no liquid secondary process waste from the offgas system.

The size of each of the two DMRs was increased from the 5-ft diameter reported in SRNL-RP-2018-00687 to 5.3-ft diameter to provide an increase in the total design waste feed rate from 7.2 gal/min (in SRNL-RP-2018-00687), prior to adding the clay mineralizing additive to increase the design feed rate to 8 gal/min (375,000 gal/month). This change was made to account for a 50% TOE assumed in this analysis.

The actual achievable feed rate is also impacted by the amount of lag storage that would be available. Lag storage capacity of 500,000 gallons was assumed in SRNL-RP-2018-00687 and here. Similar to that shown in Figure C-5 (Section C.4) for vitrification, higher or lower levels of lag storage can enable different design processing rates for the same sized treatment units (which is not included in this analysis).

The baseline FBSR alternatives (FBSR 1A and 1B) require two FBSR units in one facility to be constructed to be able to keep up with HLW processing rates and to maintain processing capacity while one unit is being maintained. The two units would share use of the interim storage tank and feed preparation facilities.

C.7 ALTERNATIVE: FBSR 2A AND FBSR 2B, MODULAR FLUIDIZED BED STEAM REFORMING ONSITE (A) AND OFF-SITE (B) DISPOSAL

Alternatives FBSR 2A and 2B consider two FBSR plants, one each for the 200 East and 200 West Areas, producing a granular, mineralized waste form. The granular waste form is formed into a geopolymer monolith in the container for alternative FBSR 2A because of the IDF compressive strength requirement. The main intent of these alternatives is to reduce the cross-site transport of untreated waste and to provide flexibility in retrieving and processing 200 West Area waste.

These alternatives are identical to FBSR 1A and 1B relative to TFPT treatment operations and for all processing and waste container size parameters. The waste is assumed to be blended, staged, and sampled in a DST and analyzed and found to be compliant with the pretreatment system such that the feed would produce an acceptable waste form after treatment. The tank waste would still be pretreated through TFPT units and collected in a lag tank to await FBSR processing. The pretreated LAW would be transferred to the FBSR plant and accumulated in the lag storage tank. (In the 200 West Area, a ~100,000-gallon lag storage tank is expected to be sufficient; in the 200 East Area, Tank AP-106 is used to provide 1 Mgal of lag storage). Since FBSR 2A requires immobilizing the granular FBSR product in a geopolymer (to meet the compressive strength requirement for IDF), the immobilized waste containers are stored for curing, decontaminated, and transported for disposal. Secondary waste disposal is in IDF.

Alternatives FBSR 2A and 2B would require a total of two FBSR facilities, one each in the 200 West and 200 East Areas. Regardless of the processing capacity in the 200 West Area, the 200 East Area immobilization process would still require two FBSR units to maintain the capacity to handle LAW liquid produced during HLW processing and interim storage while one unit is offline.

Depending on feed vectors from each area, combined with the LAW feed vector to the 200 East Area immobilization process from HLW processing and the lag storage capacity at each area, up to two FBSR units at each location (properly sized for the different feed vectors) may be needed to provide both capacity and flexibility for times of high and low feed rates. For example, the monthly average total estimated feed vector ranges from 0.16 gal/min to 8.3 gal/min (SRNL-RP-2018-00687, Figure J-7; without any adjustment for TOE). This rate represents a ~50× monthly average turndown ratio for the total feed rate for the single-location vitrification, FBSR, and grout alternatives. The combination of two FBSR units, plus lag storage, is included in alternatives FBSR 1A and 1B to account for the assumed 50% TOE, provide the needed capacity for maximum feed rates, and enable one (or both) to be turned off during periods of low feed rates.

The advantage of avoiding use of a cross-site supernatant liquid transfer line by using a modular/separate FBSR plants must be compared to the significantly more costly need for two complete facilities. Further, the added expense of a second facility would further extend the schedule because of the unavailability of funding, delaying startup and completion of the mission. Further consideration of alternatives FBSR 2A and 2B is therefore unnecessary.

C.8 ALTERNATIVE: GROUT 1A, SINGLE GROUT PLANT – ON-SITE DISPOSAL

The Grout 1A immobilization alternative is shown in Figure C-14. Disposal of the grout is assumed to be in the IDF in containers. This scenario is comparable to Case 1 from the FFRDC NDAA17 report (SRNL-RP-2018-00687).

In alternative Grout 1A, the existing DST system is assumed to be used to blend and stage the feed, comparable to the plans for System Plan Scenario 1B (ORP-11242, Rev. 9). To transport the liquid waste to the single large grout facility, a cross-site transfer line would be needed, and some remote tank farms may require transfer capabilities.

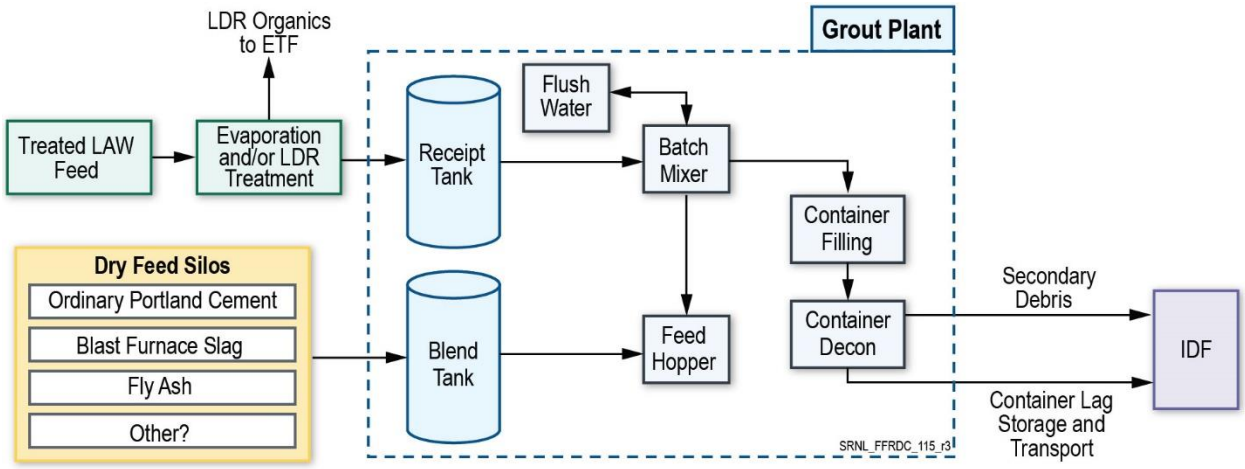


Figure C-14. Flow Diagram of Alternative Grout 1A

Like all grout alternatives, the waste is assumed to be sampled in the DST and analyzed and found to be compliant with the TFPT and LDR organic requirements such that the feed would produce an acceptable grout waste form after pretreatment and evaporation (and additional LDR organic treatment if needed) or be staged for vitrification.

The pretreated LAW would be transferred to the grout plant and accumulated in a new, purpose-built 500,000-gallon tank for lag storage. The projected process flow rate for supplemental LAW treatment is 8 gal/min, so the tank would accommodate about 40 days of lag storage.

The grout formulation is described in Volume II, Appendix A. The basic components are OPC, BFS, and FA. For on-site disposal in this alternative, a getter is added for improved ^{129}I retention.

This alternative assumes a semi-continuous batch process, where a specific mass of dry-mix feed and volume of liquid LAW are blended as a single batch and poured into containers. The filled containers are moved, and the process repeats. Between batches, the batch mixer would be cleaned with water, and any flush water is returned to a storage tank awaiting incorporation into the next batch.

The containers are assumed to be reusable 8.4 m^3 steel boxes that can be disassembled, each with a heavy-duty polypropylene bag liner. The exact container size and bag type used in a final deployment may be somewhat different than discussed here; assuming this size makes convenient comparisons to additional alternative scenarios. Minor variations in the container and liner would have minimal impact on the provided cost and schedule estimates.

After filling, the containers would be closed and the exterior decontaminated. The secondary waste generated by the decontamination process, and any contaminated hardware, would be transported and disposed in the IDF. The filled, closed containers would be staged prior to transport to IDF to allow time for curing. Once in IDF, the steel frame would be disassembled and returned to the grout plant for reuse, and the grout waste form would remain in the polypropylene liner and emplaced.

The technology parameters for the technology readiness for alternative Grout 1A are estimated to be high and could be deployed with existing technology, assuming the LDR-prohibited organics can be managed in compliance with the regulations. Additional research of formulations that have decreased leachability versus previous grouts could further improve waste form performance.

C.9 ALTERNATIVE: GROUT 1B, SINGLE GROUT PLANT – OFF-SITE DISPOSAL

The Grout 1B immobilization alternative is shown in Figure C-15. Disposal of the grout is assumed to be in containers at an off-site facility. This scenario is comparable to Case 2 from the FFRDC NDAA17 report (SRNL-RP-2018-00687).

In alternative Grout 1B, the transfer, mixing, and preparation of the waste form are the same as Grout 1A.

For Grout 1B, the cured waste form containers are shipped offsite for disposal instead of to the IDF. Once in the off-site facility, the steel frame would be disassembled and returned to the grout plant by truck/railcar for reuse, and the grout waste form would remain in the polypropylene liner and emplaced.

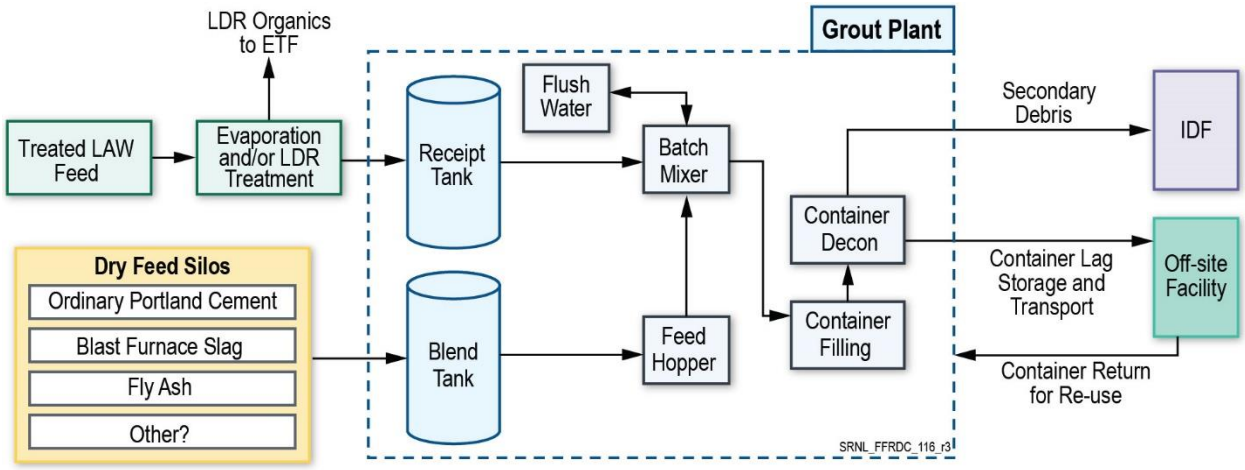


Figure C-15. Flow Diagram of Alternative Grout 1B

The technology parameters for the technology readiness for alternative Grout 1B are estimated to be high and could be deployed with existing technology, assuming the LDR-prohibited organics can be managed in compliance with the regulations.

C.10 ALTERNATIVE: GROUT 2A AND 2B, SEPARATE GROUT PLANTS FOR THE HANFORD 200 EAST AND 200 WEST AREAS WITH ON-SITE (A) OR OFF-SITE (B) DISPOSAL

Figure C-16. Aerial View of the 200 East and 200 West Area Tank Farms and Waste Treatment and Immobilization Plant

Alternatives Grout 2A and 2B consider two grouting plants, one each for the 200 East and West Areas, producing a containerized grout waste form (an aerial view of the 200 Area is shown in Figure C-16). The main intent of these alternatives is to reduce the cross-site transport of untreated waste, and as such Grout 2A and 2B are intermediate between the single grouting plant alternatives (Grout 1A and 1B) and the tank-by-tank alternative (Grout 3A and 3B).[13] Eliminating the need for cross-site transport of supernatant liquid to support this alternative would presumably decrease bottlenecks in the transfer system and would be expected to improve overall flexibility. The waste is assumed to be blended, staged, and sampled in a DST and analyzed and found to be compliant with the TFPT and LDR organic requirements such that the feed would produce an acceptable grout waste form, or be staged for vitrification.

Alternatives Grout 2A and 2B are identical to other grout alternatives relative to TFPT and LDR organic treatment operations and are essentially the same as Grout 1A and 1B for all processing and container size parameters for the 200 East Area facility. The 200 West Area facility would likely be smaller because it does not need to process surges in HLW recycle volume. The tank waste would still be pretreated through TFPT units and collected in a local tank to await grout processing. The pretreated LAW would be transferred to the grout plant and accumulated in a lag storage tank. (In 200 West Area, an ~100,000-gallon lag storage tank is expected to be sufficient; in 200 East Area, a 500,000-gallon tank is assumed to accommodate surges in LAW volume due to processing HLW). The containers are stored for curing, decontaminated, and transported for disposal. Secondary waste disposal in IDF is the same as alternative Grout 1A. Getters are included in the grout for on-site disposal (Grout 2A).

The grout formulation is described in Volume II, Appendix A. The basic components are OPC, BFS, and FA. For on-site disposal in Grout 2A in this alternative, a getter is added for improved ^{129}I retention, but not for off-site disposal in Grout 2B.

Alternatives Grout 2A and 2B evaporator and other operations may be somewhat different in that two smaller versions may be suitable for a two-plant scenario relative to a single large grout plant. Note that the 200 East plant would have to be sized to handle supplemental LAW from WTP HLW vitrification, while the 200 West plant would likely be smaller and have a lower capacity requirement.[14]
The condensate from 200 West Area would have to be transported to LERF/ETF by truck (where ETF is already equipped to receive waste by truck).

[13] To give a sense of scale (see Figure C-16), the "main" 200 East (A and C Farms) and 200 West (S and U Farms) clusters are separated by about 6 miles; while the more "remote" 200 East (B Farm) and 200 West (T Farm) clusters are each about 1.3 miles from the main 200 East and 200 West Area clusters, respectively.

[14] Both grouting plants might be relocatable. If relocatable, a single move of the 200 West grouting plant, from the S Farm to the T Farm; and/or a single move of the 200 East grouting plant from the A Farm to the B Farm, might be cost effective.

However, if some portion of the waste is resistant to the processes selected for LDR organic treatment (e.g., evaporator and low-temperature oxidation), that waste is assumed to be diverted to the WTP LAW melter facility for processing via the transfer lines used to transport supernatant liquid to the 200 East tank farms and the WTP.

For alternatives Grout 2A and 2B, disposal of the grout waste form is onsite or offsite, respectively. The flowsheet schematics are assumed to be the same as those shown in alternative Grout 1A and 1B, and as shown in Figure C-14 and Figure C-15 (Sections C.8 and C.9, respectively), although with smaller equipment sizes. The slight difference in the shipping of the grouted supplemental LAW containers from the 200 West grouting plant to the IDF is insignificant. Other details for on-site or off-site shipping and disposal are the same as alternatives Grout 1A and 1B, respectively. Note that these alternatives have the option of beginning treatment in the 200 East or 200 West Areas, independent of the other.

C.11 ALTERNATIVE: GROUT 2C, SEPARATE GROUT PLANTS FOR THE HANFORD 200 EAST AND 200 WEST AREAS WITH TECHNETIUM/IODINE REMOVAL AND ON-SITE DISPOSAL

Removal of ^{129}I and/or ^{99}Tc is considered alternative Grout 2C, where all other flowsheet assumptions are consistent with alternative Grout 2A (and would eliminate the need for getters). After TFPT treatment, technetium and iodine removal processes (described in Sections C.15.1 and C.15.2, respectively) are used to remove these radionuclides prior to LDR treatment, grouting, and on-site disposal of the supplemental LAW waste form. The separated technetium and iodine are disposed as a secondary waste form in a commercial off-site facility.

C.12 ALTERNATIVE: GROUT 3A, INDIVIDUAL GROUT PLANTS FOR EACH TANK FARM OR TANK FARM GROUP WITH ON-SITE (3A) OR OFF-SITE (3B) DISPOSAL

This alternative uses mobile or multiple small batch TFPT, LDR treatment, and grout plants to treat supernatant liquid at each tank farm or tank farm grouping, disposing the immobilized waste either onsite (3A) or offsite (3B). This alternative does not require a cross-site transfer line for supernatant liquid that is compatible with grouting. The liquid is immobilized in mobile or multiple small batch grout plants and poured into containers. The containerized grouted waste could then be transported and disposed in the IDF (Grout 3A) or sent to an off-site facility for disposal (Grout 3B). If some portion of the waste is resistant to these treatments to remove the organics, that waste is assumed to be diverted to the WTP LAW melter facility for processing.

The grout formulation is described in Volume II, Appendix A. The basic components are OPC, BFS, and FA. For on-site disposal in Grout 3A in this alternative, a getter is added for improved ^{129}I retention, but not for off-site disposal in Grout 3B.

Modular treatment units would be installed at the individual tank farms or tank farm groups. These treatment units could be skid-mounted systems operated by a vendor or the tank farms contractor. Waste is retrieved and fed directly to the TFPT/LDR and grouting processes. The waste is assumed to be sampled in the tank and then analyzed and found to be compliant with the TFPT and LDR organic requirements such that the feed would produce an acceptable grout waste form or be staged for vitrification. The pretreated LAW would be accumulated in an above-ground tank module on the order of 10,000 gallons for lag storage. The projected process flow rate for supplemental LAW treatment is 8 gal/min, so the tank would accommodate about 1 day of lag storage. When the treatment of the targeted tanks has been completed, treatment modules could be redeployed to other tank farms or, where more economical, simply replaced, thus maximizing the investment made in the equipment.

This alternative assumes the same process and steps for preparing containerized grout as Grout 1A, but the steps occur in two facilities in separate on-site locations.

Technical maturity for the immobilization process is high and could be performed with existing technology. Portable grout plants have been deployed at SRS, although for use in facility stabilization and not immobilization of treated supernatant liquid. At least one mobile evaporator design has been fabricated and tested but has not been deployed in radioactive service, albeit not for technical reasons.

The process flowsheet is shown in Figure C-17. Since treatment will be accomplished near the tanks, a cross-site transfer line for supernatant liquid is not necessary for waste that is compatible with the grouting process. All secondary liquid waste generated by the evaporation process is assumed to be handled by the available site facilities such as ETF. Transportation to ETF will likely occur by truck. The ETF is already equipped with facilities to receive waste transported by truck (Note: the receipt tank is smaller for this alternative vs. other alternatives).

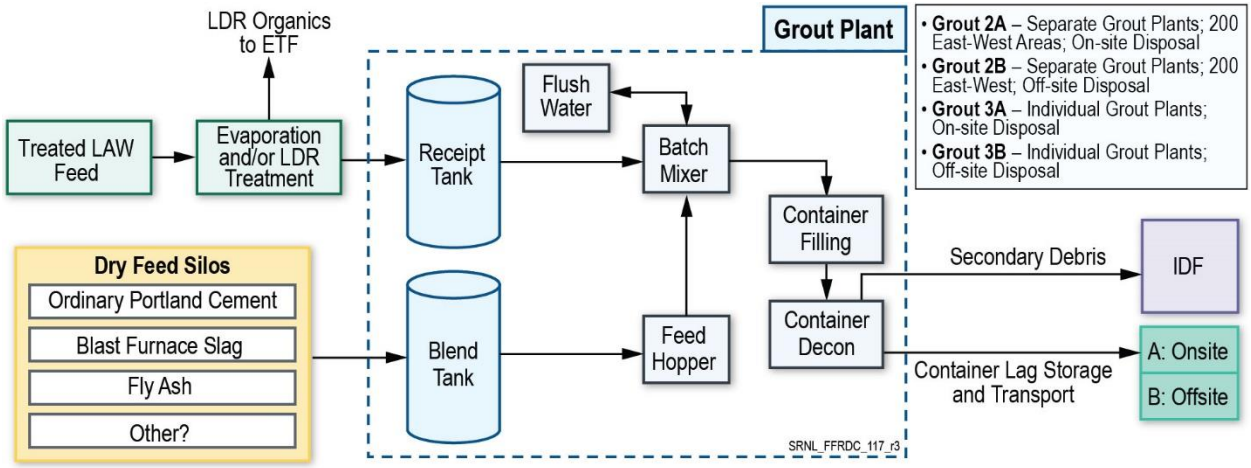


Figure C-17. Flow Diagram for Alternatives Grout 3A and 3B

Alternative Grout 3A

Disposal of the grout is assumed to be in containers in the IDF. This scenario is comparable to Case 1 from the NDAA17 report (SRNL-RP-2018-00687). This alternative assumes that the grouted waste form will be packaged in a similar manner as Grout 1A (using 8.4 m^3 polypropylene bags inside a reusable steel box that can be disassembled for reuse) and the grouting process will use the same formulations assumed in alternative Grout 1.

Alternative Grout 3B

This alternative also assumes that the grouted waste form will be packaged in a similar manner as Grout 1A (8.4 m^3 polypropylene bags inside a reusable steel box that can be disassembled) and the grouting process will use the same formulations assumed in alternative Grout 1A. The grouted forms would be transported for disposal to an existing permitted off-site facility, with the same assumptions as Grout 1B.

Once removed, the waste cannot be returned to the single-shell tanks (SST). The individual grout plants would also be accompanied by individual TFPT/TSCR systems, which contain filters. The TFPT/TSCR filter must be flushed periodically to remove solids, which cannot be sent to the SSTs, requiring a tank for storage. Essentially, the process would require construction of waste receiving facilities (WRF) and pretreatment and treatment capacity near each group of tanks. The TFPT/TSCR system, along with an LDR treatment system and the ability to provide utilities, containment, seismically qualified pads, WRFs, and primary and secondary waste/effluent staging, handling, and trucking for each tank farm/grouping would likely also be needed (although some of these would be reusable if designed to be mobile). The cost and time of constructing (and perhaps moving) all equipment for each group of tanks negates the

advantages of these alternatives and would add cost and construction time to deploy and mobilize. Given that Grout 2A and 2B avoid this cost and effort, those alternatives would be considered superior to Grout 3A and 3B. For these reasons, alternatives Grout 3A and 3B have been rejected and no further evaluation is recommended.

C.13 ALTERNATIVE: GROUT 4A AND 4B, OFF-SITE VENDOR FOR GROUTING WITH ON-SITE (4A) OR OFF-SITE (4B) DISPOSAL

This alternative uses an off-site vendor to immobilize the treated supernatant liquid. The grouted waste could then be sent to an off-site facility for disposal or returned to the Hanford Site for disposal in the IDF. After removal of ^{137}Cs and ^{90}Sr in TFPT and LDR organic treatment, the treated supernatant liquid is shipped offsite in liquid form.[15] Multiple vendors are currently available that have the technical ability to grout the waste, and one or more could be used for this service. Though not analyzed, the off-site vendor could potentially treat the LDR organics instead of treating onsite.

In alternatives Grout 4A and 4B, the existing DST system is assumed to be used to blend and stage the feed. The logic assumes retrievals are routed through Tanks SY-102 and SY-103, and Tank SY-101 is the feed tank to the TFPT. A cross-site transfer line specifically for this alternative would not be needed for waste that is compatible with grouting. The waste is assumed to be sampled in the DST and then analyzed and found to be compliant with the TFPT and LDR organic requirements such that the feed would produce an acceptable grout waste form, or be staged for vitrification. This alternative could provide an early start and/or supplemental capacity for grout stabilization of the LAW. An early start for supplemental treatment of LAW using this alternative, with eventual replacement/supplement with on-site grout facilities, could potentially reduce overall mission costs and duration and is addressed in Section C.16 (alternative Grout 6).

The grout formulation is described in Volume II, Appendix A. The basic components are OPC, BFS, and FA. For on-site disposal in Grout 4A in this alternative, a getter is added for improved ^{129}I retention, but not for off-site disposal in Grout 4B.

The process flowsheet for Grout 4A/4B is shown in Figure C-18 (where LDR treatment is assumed in this alternative). This alternative can be used for both a centralized facility that pretreats the supernatant liquid or for modular facilities at each tank farm; however, this alternative is more suited for at-tank or at-tank-farm systems. A cross-site transfer line specifically for this alternative for supernatant liquid that is compatible with grouting is not necessary assuming the pretreatment is not centralized.

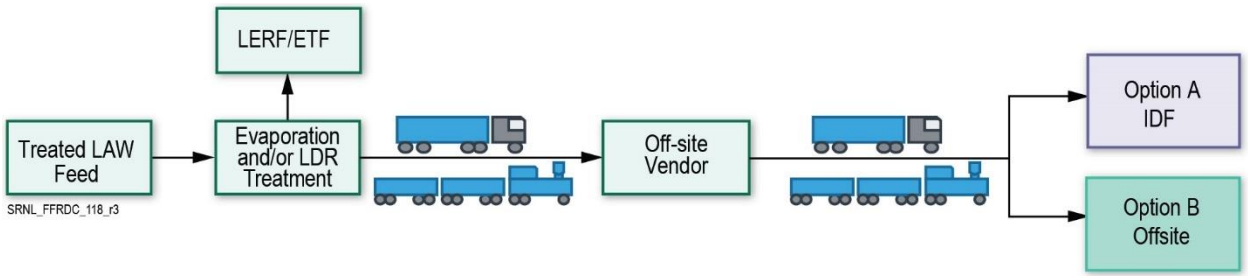


Figure C-18. Flow Diagram for Alternatives Grout 4A and 4B

[15] The ability to ship pretreated liquid tank waste at a small scale (3-gallon proof of concept) was demonstrated during the Hanford Test Bed Initiative (DOE-EM, 2018).

All secondary liquid and solid waste generated by the immobilization process is assumed to be handled by the off-site vendor. The pretreated LAW would be transferred to a ~150,000-gallon tank for lag storage. The projected process flow rate for supplemental LAW treatment is 8 gal/min, so the tank would accommodate a 10-20 days of lag storage.

This alternative assumes a semi-continuous batch process performed by the vendor, where a specific mass of dry-mix feed and volume of liquid LAW are blended as a single batch and poured into a container or containers. The filled containers are moved, and the process repeats.

Consistent with the other alternatives for containerized grout, the containers are assumed to be reusable 8.4 m^3 steel boxes that can be disassembled, each with a heavy-duty polypropylene bag liner. The exact container size and bag type used in a final deployment by the vendor may be somewhat different than discussed here; assuming this size makes convenient comparisons to additional alternative scenarios. Minor variations in the container and liner would have minimal impact on the provided cost and schedule estimates but will ultimately be consistent with the basis defined in the PA and incorporated into the waste acceptance criteria for the on-site or off-site disposal alternative.

Technical maturity for the immobilization process is high and could be performed with existing technology, assuming that the LDR organics can be removed by a separate process.

This alternative postpones the cost of a grout plant (capital, operating, and disposition); instead, a fee is paid per gallon for immobilization of the waste. Delaying the initial capital cost for an on-site supplemental LAW treatment facility could be advantageous to avoid exceeding yearly spending limits and could allow an earlier start for processing (see hybrid alternative Grout 6).

For alternative Grout 4A, the grouted waste packages are shipped from the vendor to the IDF. For alternative Grout 4B, the vendor that produces the grouted waste form may not be located at the disposal site and the compliant grouted packages would then be sent from the vendor to the off-site facility(ies) for disposal. If the vendor that performs grouting is located at the disposal site, the grouted waste does not need additional transport. In either case, the waste is emplaced at the disposal site (e.g., Energy*Solutions* [Clive, Utah] and/or WCS [Andrews, Texas]). Since the off-site contractor is handling or coordinating both immobilization and disposal in alternative Grout 4B, the contractor could choose both the immobilization technique and the final packaging size and type, although for purposes of evaluating this alternative, the same size package and transportation details were assumed. Secondary wastes from grouting are estimated to be small, and standard commercial practice is for the vendor to handle management and disposal.

Early Start

The off-site treatment alternatives have the potential for an early start since a capital project is not needed prior to beginning supplemental LAW treatment. Off-site vendors currently have the production capacity to begin immobilizing decontaminated tank waste. Construction of the TFPT, LDR treatment, and a load-out station onsite would be needed, along with permitting for processing and disposal. This potential for early start was adopted for alternatives Grout 4B and 6 in the detailed comparative evaluation of the four selected alternatives.

C.14 ALTERNATIVE: GROUT 5A AND GROUT 5B, SINGLE GROUT PLANT WITH ON-SITE MONOLITH (5A) OR CONTAINERS IN VAULT (5B) DISPOSAL

The grout immobilization alternative, Grout 5, is depicted in Figure C-19. The grout is either poured as a slurry into the on-site vault to produce a monolith (5A) or is poured into containers, which are then transported and emplaced in an on-site vault (Grout 5B). Disposal of the grout is assumed to be in large vaults, referred to as grout disposal units (GDU), analogous to the newest, mega-volume >30 Mgal Saltstone Disposal Units (SDU) at SRS (SRR-CWDA-2019-00001, *Performance Assessment for the Saltstone Disposal Facility at the Savannah River Site*),[16] with the exact geometry of the vault to be determined depending on the grouted waste form processing option (discussed below). Compared to disposal of containers in IDF, this scenario would reduce the interaction of the grouted waste form with the surrounding environment. The vault's large size has minimal surface area (relative to volume) to interact with the surrounding environment and has engineered controls that thereby reduce the potential for leaching, release, and transport of constituents of concern to the environment. As described below, this alternative provides considerable flexibility in processing and disposal pathways based on timing and waste characteristics and allows the ability to transition efficiently among different alternatives.

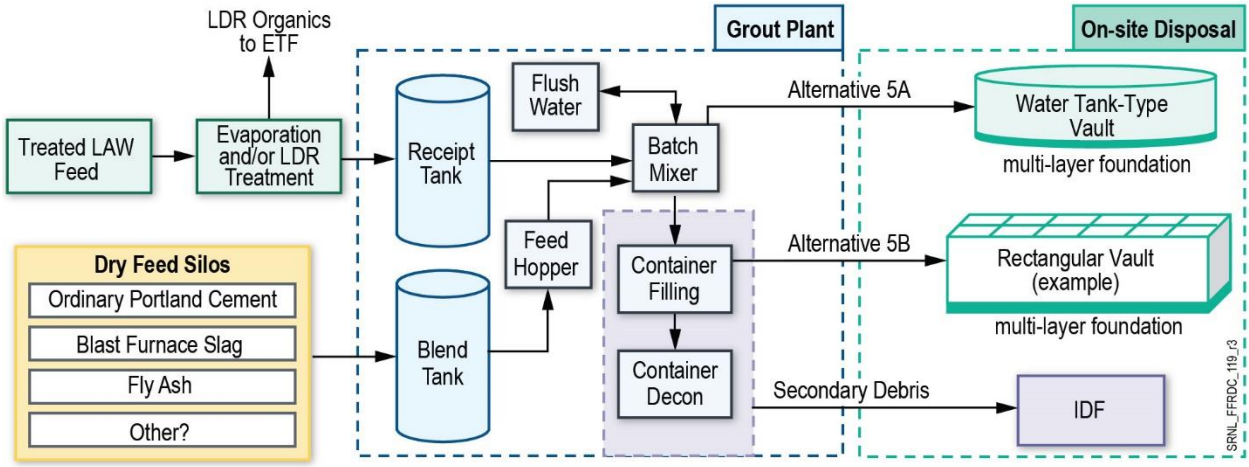


Figure C-19. Flow Diagram of Alternative Grout 5 (5A – Large Grout Plant and Water-Tank Vault | 5B – Modular Grout Plant(s))

[16] Construction of the first mega-volume SDU 6 at SRS was completed in May 2017 and began receiving waste in August 2018. SDUs 7 through 12 have been approved, with two currently under construction.

In alternatives Grout 5A and 5B, the existing DST system would be used to blend and stage supernatant liquid and followed by TFPT and LDR organic treatment. This alternative requires large vaults to be constructed in the 200 East Area (where both the WTP and IDF are located), and uses the cross-site supernatant liquid transfer line and transfer capabilities to transfer waste from the remote tank farms.[17] The waste is assumed to be sampled in the DST system and analyzed, and when found to be compliant with the TFPT and LDR requirements such that the feed would produce an acceptable grouted waste form, pretreated via TFPT to remove ^{137}Cs (with ^{90}Sr and some actinides also removed), evaporated, and any fraction requiring additional treatment treated for LDR organics or the waste is sent for WTP LAW processing. The resulting pretreated LAW would be transferred to the grout plant(s). A large grout facility (like the SRS Saltstone Production Facility) would be constructed to support the large waste tank-type vault, the treated waste would be accumulated in a tank up to 500,000 gallons for lag storage (similar to assumption in alternative Grout 1A).[18] The projected process flow rate for supplemental LAW treatment is 8 gal/min (see alternative Grout 1A), so a 500,000-gallon tank would accommodate approximately 40 days of lag storage.

This alternative is based on a semi-continuous batch grout process, where the liquid LAW is mixed with cementitious materials (e.g., cement, FA, and slag [BFS]) and then pumped:

- **Alternative Grout 5A** – In lifts for the large, water tank-type vault similar to SDU 7 through 12 at SRS, where the grout solidifies into a monolithic, solid LLW form.
- **Alternative Grout 5B** – Into 8.4 m^3 polypropylene supersacks initially contained in reusable steel boxes that can be disassembled. After filling, the containers would be closed and the exterior decontaminated. The filled, closed containers would be staged to allow time for curing. The steel frame would be disassembled and returned to the grout plant for reuse, and the grout waste form would remain in the polypropylene liner for disposal in large vaults (with exact geometry to be determined) using, for example, a gantry crane.[19]

The grout formulation and additives would likely differ for the above alternatives because of the need for flowability for pumping long distances and likely increased load-bearing capacity for alternative Grout 5A. Alternative Grout 5B has benefits in higher flexibility of grout formulations because of the absence of the need for flowability. The grout formulation is described in Volume II, Appendix A. The basic components are OPC, BFS, and FA. No getter for ^{129}I is added, since the vault and cap system are designed to retain the contaminants.

[17] Alternatively, if one or more large vaults were constructed in both the 200 East and 200 West Areas; this alternative would not require using the cross-site supernatant liquid transfer line for waste compatible with grouting but would require TFPT, LDR treatment, and grout plants in both the 200 East and 200 West Areas and the cross-site transfer line is needed for other purposes. An additional consideration for this alternative entails whether a large vault containing a monolithic waste form would necessarily dictate a large grout facility (e.g., SRS Salt Processing Facility [SRNL-STI-2019-00009, *Review of Cementitious Materials Development and Applications that have Supported DOE-EM Missions: Waste Treatment, Conditioning, Containment Structures, Tank Closures, Facility Decommissioning, Environmental Restoration, and Structural Assessments*]) or could smaller (and perhaps mobile) grout facilities provide sufficient process capacity to efficiently and effectively fill a large vault (i.e., necessarily using lifts) without impacting grout performance. This consideration would be obviated by assuming that smaller, modular (on- or off-site) grout facilities would be paired with filling 8.4 m^3 polypropylene supersacks inside reusable steel boxes (see alternative Grout 3) that could then be (depending on timing and waste characteristics) disposed in large vaults (with geometry to be determined). Note that this alternative would be analogous to alternative Grout 3A for on-site disposal of the supersacks in the IDF or to alternative Grout 3B for off-site disposal (Clive Disposal Facility and/or WCS). This hybrid alternative would thus provide a great deal of flexibility in the disposal pathway based on timing and waste characteristics.

[18] Alternatively, a relocatable (and perhaps mobile) grout facility (alternative Grout 3) would require different lag storage requirements (at a volume or volumes and configuration to be determined).

[19] Depending on timing and waste characteristics, the supersacks could also be disposed of onsite in IDF (alternative Grout 1A) or sent offsite (Clive Disposal Facility and/or WCS) for disposal (alternative Grout 1B) for on-site grout generation. For off-site vendor grout generation, these alternatives correspond to alternatives Grout 5A and 5B, respectively.

Between batches, the batch mixer would be cleaned with water, and any flush water returned to a storage tank awaiting incorporation into the next batch. Any secondary debris waste generated by the decontamination process, and any contaminated hardware, would be transported and disposed of in the IDF.

The large vaults are assumed to be constructed of high strength, low permeability concrete where the alternatives differ in the vault internals and how the grout would be produced and stored in the vault. The vault floor would sit atop a multi-layer foundation (Figure C-19) similar to that for SRS SDUs 7 through 12; the layers include a specially engineered geosynthetic clay liner and a high-density plastic liner (similar to that used in commercial landfill applications) sandwiched between two concrete layers called "mud mats." The mud mats serve as the foundation for the concrete structural base slab and to protect the leakage detection system. The vault and engineered liners work together to further limit release and environmental migration of contaminants.

Specific assumed vault dimensions would be:

- **Alternative Grout 5A** –The grout is pumped into the large water-tank type vault assumed to be 375 ft in diameter, 43 ft high, and can hold approximately 33 Mgal (125,000 m^3) of grout.[20]
- **Alternative Grout 5B** – Disposal of the grout supersacks is assumed to be in large disposal vaults with geometry to be determined. Backfill material fills the spaces among the waste supersacks. Assuming a rectangular vault to be 600 ft long × 200 ft wide (divided into twelve 100-ft × 100-ft cells) × 30 ft tall,[21] the vault could contain as much as 17 Mgal (65,500 m^3) of grout (and could be redesigned to contain more or less grout). The vault would comprise individual cells constructed of concrete.

Although not expected, if in the future the need to remediate the waste became necessary, an additional robust cap or barrier could be added since the vault covers a relatively compact area. Alternatively, retrieving the material for unforeseen reasons is also considered plausible,[22] but costly, to retrieve the large monolith (Grout 5A) in sections using current techniques. Retrieval of the containerized grout (Grout 5B) would also be plausible, and presumably be more readily achieved. The retrieved waste is assumed to be disposed in a different location and/or facility.

[20] These are the dimensions of SDU 6 and later large (or "mega") water tank design units at SRS (SRR-CWDA-2019-00001).

[21] These are the dimensions of an existing SRS vault. The rectangular vault and cell dimensions considered for the Hanford Site application would likely be revised to better accommodate the aspect ratios of the supersack.

[22] If found necessary, sections of the large grout monolith can be retrieved. One analog for the grout monolith is a nuclear reactor biological shield, which surrounds the reactor pressure vessel and is made of concrete; removal of a contaminated reactor biological shield has occurred in numerous instances. Past experience suggests that diamond wire cutting and water jet cutting are the best suited techniques for biological shield cutting (Laraia, 2021). The major advantage of diamond wire or water jet cutting is that airborne contamination can be reduced to the point that HEPA-filtered ventilation would not be required. However, both techniques would generate contaminated liquid waste that must be managed. For a huge structure like a biological shield or large grout monolith, techniques with limited cutting size (e.g., explosions, thermic lance, saws) would not be considered suitable.

Additional defense-in-depth measures (both internal and external[23]) could be added as needed to ensure meeting the criteria in the PA. For example, the use of a rectangular vault in alternative Grout 5B (versus direct emplacement of the supersacks in the IDF) would further limit the exposure of the grouted waste forms to the environment and thus contaminant release and transport. These defense-in-depth measures are not formally evaluated as alternatives or options in the decision framework.

The technology readiness for alternatives Grout 5A and 5B is estimated to be high and could be deployed with existing technology.

C.15 ALTERNATIVE: GROUT 1C, SINGLE GROUT PLANT WITH TECHNETIUM/IODINE REMOVAL – ON-SITE DISPOSAL AND GROUT 2C, SEPARATE GROUT PLANTS FOR THE HANFORD 200 EAST AND 200 WEST AREAS WITH TECHNETIUM/IODINE REMOVAL – ON-SITE DISPOSAL

Removal of ^{129}I and/or ^{99}Tc are considered alternative Grout 1C, where all other flowsheet assumptions are consistent with alternative Grout 1A (and would eliminate the need for getters). After TFPT and LDR treatment, technetium and iodine removal processes (described in Sections C.15.1 and C.15.2, respectively) are used to remove these radionuclides prior to grouting and on-site disposal of the immobilized LAW. The separate technetium and iodine are disposed of as a secondary waste form offsite. Similarly, a sample-and-send approach is employed for alternative Grout 1D (described in Section C.15.3). In alternative Grout 1D, the waste is sampled and analyzed for ^{129}I and/or ^{99}Tc. After grouting the waste, grout containers with lower than a threshold concentration of these radionuclides would be disposed of onsite, and those with higher than threshold concentration would be disposed of offsite. The threshold limit has not yet been defined, but would be tied to the risk budget tool used for the PA.

Alternatives Grout 1C and 2C are identical to alternatives Grout 1A and Grout 2A, except a process is used to remove technetium and iodine from the LAW after TFPT treatment. The technetium and iodine removal technologies are described in the subsections that follow. Discussion of the subsequent immobilization step for Grout 1C and 2C is provided in the descriptions for Grout 1A and Grout 2A, respectively. Note that technetium and iodine partition to the offgas and then to the recycle stream from the first LAW melters, which are blended with fresh LAW feed. For these alternatives, the partitioning of radionuclides requires that the technetium and iodine removal occurs just prior to supplemental LAW immobilization from the combined stream. If iodine cannot be removed, getters are assumed used in the waste form instead for alternatives Grout 1A, 2A, 3A, and 4A.

C.15.1 Technetium Removal

A technology for removal of ^{99}Tc from LAW was developed and matured as a pretreatment step for the Hanford WTP LAW vitrification flowsheet (McCabe et al., 2001, WSRC-TR-2003-00098, *Multiple Ion Exchange Column Runs For Cesium and Technetium Removal From AW-101 Waste Sample(U)*; Burgeson et al., 2011; PNNL-25834, *Options for the Separation and Immobilization of Technetium*). However, the technetium removal step was removed from the flowsheet in 2003, albeit not because of technical maturity or effectiveness.

[23] In addition to using a large monolith in alternative Grout 5A (low surface area to volume ratio) to reduce potential interaction of the bulk of the grouted waste form with the surrounding environment, other types of coatings, liners, and grout applications may reduce impacts even further (e.g., a coating was applied to SDU 6 at SRS to provide sufficient water tightness). The application of clean, reducing grout layers (acting as diffusion barriers and additional reductive capacity) in either alternative Grout 5A or 5B could significantly improve overall vault system performance. Additional research of grout formulations that have decreased leachability versus previous grouts could further improve waste form performance. Other options include getters in the backfill material and closure cap or engineered covers. In addition, the proposed ^{99}Tc and ^{129}I removal alternatives would provide even greater flexibility in waste treatment and disposal pathways.

The approach developed for WTP was the use of a molecular recognition technology resin, SuperLig®[24] 639, to remove TcO_4^-. In this application, the resin is loaded into columns. After treatment to remove ^{137}Cs and ^{129}I, the treated LAW is pumped through the columns to remove the ^{99}Tc. The absorbed ^{99}Tc is subsequently removed from the resin by elution with warm water and immobilized separately. The columns are regenerated and returned to service for another loading-elution cycle. The treated LAW is then treated for LDR organics, if needed, and sent for immobilization.

SuperLig® 639 can selectively remove 99+% of the pertechnetate ion from LAW. The technical maturation activities that were completed included testing with several actual tank waste samples and with simulants:

- Burgeson et al. (2011), "Removal of Technetium from Hanford Tank Waste Supernates"
- McCabe et al. (2001), "Comprehensive Scale Testing of the Ion Exchange Removal of Cesium and Technetium from Hanford Tank Wastes"
- WSRC-MS-2001-00760, *Technetium Removal from Hanford and Savannah River Site Actual Tank Waste Supernates with SuperLig® 639 Resin*
- WSRC-TR-2000-00419, *Small Scale Ion Exchange Removal of Cesium and Technetium from Envelope B Hanford Tank 241-AZ-102*
- WSRC-TR-2000-00420, *Intermediate-Scale Ion Exchange Removal of Cesium and Technetium from Hanford Tank 241-AN-102*
- WSRC-TR-2000-00424, *Tank 241-AZ-102 SuperLig® 639 Technetium Ion Exchange Eluate Evaporation Study*.

Testing was also performed to demonstrate chemical stability during multiple cycles with actual tank waste (WSRC-TR-2003-00098 *Multiple Ion Exchange Column Runs for Cesium and Technetium Removal from AW-101 Waste Sample(U*). Simulant testing with full height columns has demonstrated 99% removal of perrhenate (surrogate for pertechnetate) (WSRC-TR-2000-00302, *Summary of Testing of Superlig 639 at the TFL Ion Exchange Facility*). No further development is believed needed to prove viability for full-scale deployment of the removal technology. Depending on the selected fate of the disposal path of the technetium, development work may be needed for the final waste form.

A conceptual schematic is shown in Figure C-20. A two-column carousel of the SuperLig® 639 resin can remove 99% of the technetium from approximately 300 bed volumes of waste for each loading cycle before saturation. After the absorption step, the resin is eluted with about 20 bed volumes of warm water, reconditioned with caustic, and then returned to service for reuse multiple times. The water eluate contains the pertechnetate, and the original flowsheet involved evaporation to concentrate the eluate, and then incorporating it into the HLW melter feed where it would be vitrified for disposal as HLW glass. Evaporation and incorporating the technetium from actual Hanford waste into HLW glass was demonstrated at the laboratory scale (WSRC-TR-2000-00424, WSRC-MS-98-00447, *Production of a High-Level Waste Glass from Hanford Waste Samples*). The evaporator condensate would be reused as eluate. However, during HLW vitrification, a substantial portion of the technetium would vaporize from the HLW melter and would be scrubbed from the vapor and into the melter condensate for return to the aqueous LAW phase, where the condensate would be processed for Tc removal again and recycled to the HLW melter. Further steps could be taken to improve retention of Tc in HLW melter for limited campaigns, if found necessary, such as reduced bubbling rate and more electrochemically reducing glass chemistry.

[24] SuperLig is a trademark of IBC Advanced Technologies, Inc., American Fork, Utah.

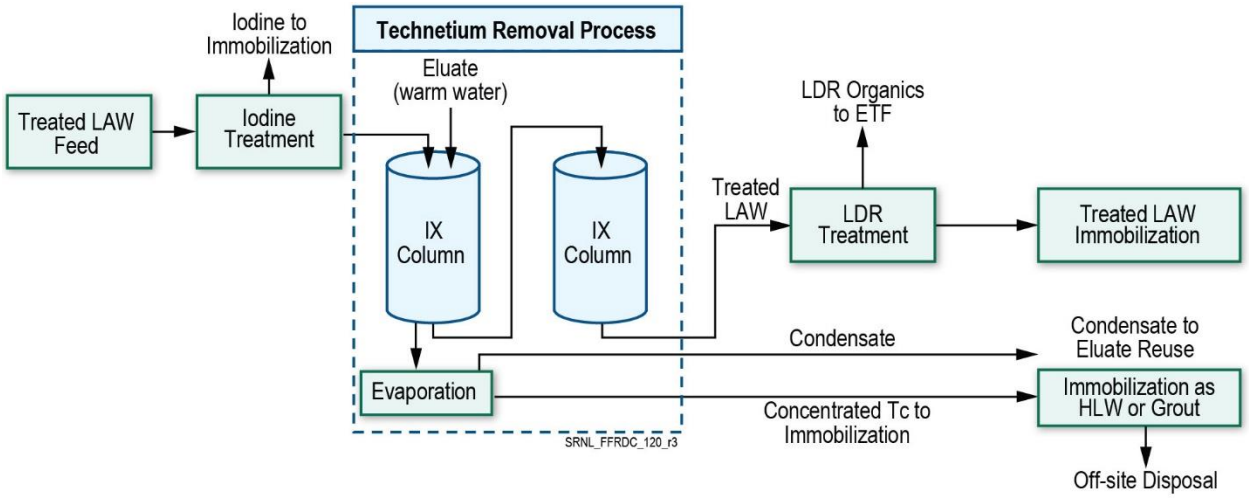


Figure C-20. Technetium Removal Concept

Existing technology could also potentially immobilize the eluate as a secondary grout waste, although this has not been specifically demonstrated. The technetium-containing grout would be a very small volume and could be disposed as a special waste form assumed disposed offsite. While not demonstrated, the technology for this exists. Although this is low technical maturity because specific testing has not been done, the chemistry is understood and there is high confidence that the process could be accomplished with minimal technology development.

The alternative assumes evaporation and immobilization, but there are other methods. Concentrating the technetium from the eluate could also be done by reducing the soluble Tc(VII) as pertechnetate to the insoluble Tc(IV) oxide and removing it from the bulk of the liquid eluate by settling or filtering.

This alternative eluate treatment is not shown in Figure C-20. The reductive precipitation of technetium has been demonstrated at the laboratory scale in similar low ionic strength waste streams using either Stannous chloride ($SnCl_2$) (SRNL-STI-2015-00677, 2015, *Laboratory Optimization Tests of Technetium Decontamination of Hanford Waste Treatment Plant Direct Feed Low Activity Waste Melter Off-Gas Condensate Simulant*) or Zero Valent Iron (ZVI) (Boglaienko et al., 2019). Presumably, these methods could be readily adapted to precipitate the ^{99}Tc from the eluate, allowing it to be settled or filtered and sent as a slurry for immobilization as HLW glass or a grout waste form that would be disposed of offsite. The eluate aqueous phase leftover after technetium precipitation and removal would be blended with LAW for immobilization. Regardless of whether the ^{99}Tc in the eluate is concentrated by evaporation or precipitation, these processes are considered mature or are readily matured for deployment for immobilization of the ^{99}Tc as a glass or grout waste form. In all cases, off-site disposal of the concentrated technetium in a glass or grout waste form is viable.

However, only the portion of technetium that is present as pertechnetate ion can be removed by the SuperLig® 639 resin. Tanks are known to contain varying fractions of soluble technetium that is present as a species other than pertechnetate, known as non-pertechnetate. Any portion that is present as any soluble species other than pertechnetate would pass through the resin column unhindered and remain in the supplemental LAW stream. This impact of non-pertechnetate is discussed further in Volume II, Appendix E. For this alternative, an analysis of the tank waste liquid would be performed prior to TFPT treatment to determine the amount of pertechnetate and non-pertechnetate. Those tank liquids with a concentration of non-pertechnetate above a selected threshold would be sent to the LAW melter instead of grouting, or a method to convert non-pertechnetate to pertechnetate would be developed and used prior to ion exchange treatment.

Although the resin is reused, after multiple cycles, the resin degrades and needs replacement. The spent resin can be thoroughly eluted and disposed of as LLW in IDF. This disposition was the original pathway for disposition of this spent resin (and is the pathway for the resin used for cesium removal in the WTP Pretreatment Facility).

Removing ^{99}Tc from the LAW stream could avoid disposing a sizeable fraction of it in the inventory of the supplemental LAW waste form, if is diverted to another waste form. More details on alternatives for technetium sequestration and/or removal are provided in SRNL-STI-2020-00228, *Evaluation of Technologies for Enhancing Grout for Immobilizing Hanford Supplemental Low-Activity Waste (SLAW)*.

Table C-6 summarizes the status of technetium removal technology.

Table C-6. Technetium Removal Technology

Knowns[a]	Unknowns
• Demonstrated 99% removal of pertechnetate with actual wastes • Demonstrated >99% removal of perrhenate from simulant at full bed height • Resin can be produced by vendor • Elution method effectiveness • Demonstration of eluate evaporation • Demonstration of vitrification of technetium eluate in HLW glass • Spent media characterization	• Inventory of non-pertechnetate • If vitrification is not selected for separated technetium disposition path, development of a waste form would be needed • Behavior of non-pertechnetate in a grout waste form

[a] Assumes SuperLig™ 639 resin is used.

HLW = high-level waste.

C.15.2 Iodine Removal

Unlike technetium, iodine removal from LAW has never been part of the WTP flowsheet. Historically, a significant portion of the iodine was assumed to be retained in the glass, and any iodine that partitioned to the vapor would be captured by the secondary offgas system. This assumption led to minimal testing being performed over the years to examine methods to remove it from LAW. Limited testing with simulants has been performed with silver-based materials that could remove iodine from LAW (Asmussen et al., 2016), and one test with actual SRS tank waste and a resin (SRNL-STI-2013-00538, *Scoping Tests of Technetium and Iodine Removal from Tank Waste Using SuperLig® 639 Resin*). The pretreatment technology for iodine removal that is most effective is a silver-containing zeolite-based media that precipitates the ^{129}I (and all other iodine isotopes) as AgI. Other sorbents are considered to not be selective enough for iodine or have sufficient capacity to be useful. The process is assumed to be implemented to treat the LAW after TFPT and before technetium removal (if applicable) and LDR organic removal processing. The media would either be loaded in a pair of packed bed ion exchange columns or would be contacted with the liquid as a slurry, such as in a continuous stirred tank reactor (CSTR). Selection of the appropriate method would be determined by a technology development program. A conceptual flowsheet for the ion exchange column configuration is shown in Figure C-21. The media would remove iodine species through precipitation onto the zeolite (i.e., as silver iodide). The iodine-depleted, treated LAW would then be transferred for grout immobilization. The ^{129}I-loaded media would be sluiced to another container and disposed of as secondary waste. Fresh media is loaded into the columns or CSTR for the next cycle. Alternatively, the media may remain in the columns, with the columns simply drained, rinsed, dried, and stored, and replaced with new columns.

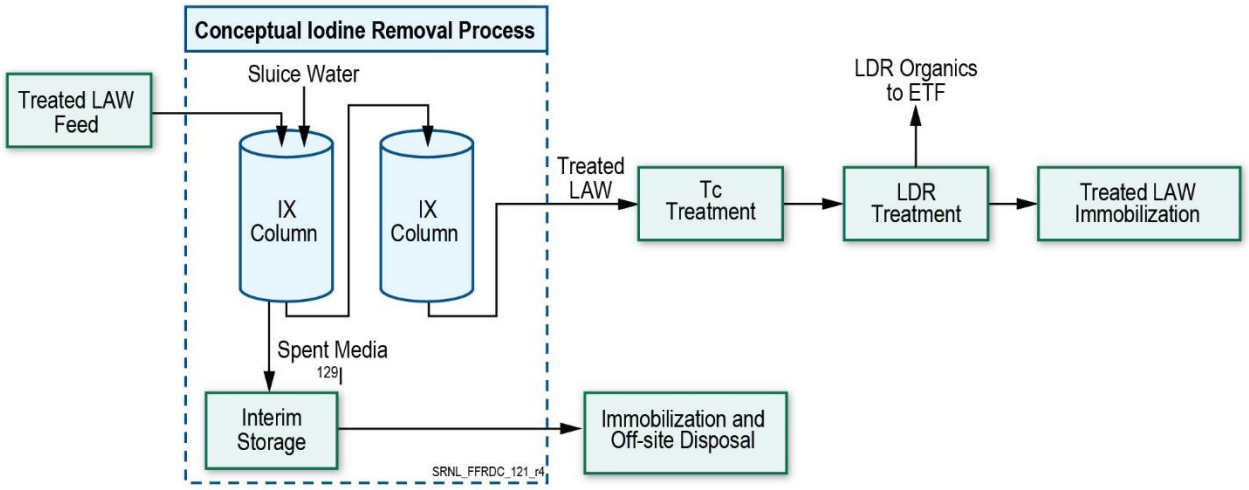


Figure C-21. Iodine Removal Concept

Laboratory tests have been conducted using several Ag-containing materials as selective removal agents, or getters, for iodine removal from deionized water and a liquid Hanford LAW simulant (Asmussen et al., 2016). These getter materials included commercially obtained Ag-impregnated activate carbon (Ag–C) and Ag exchanged zeolite (Ag–Z), and laboratory-synthesized argentite. Anoxic batch experiments with 10 g/L sorbent dosing in LAW simulant indicated that Ag–Z significantly outperformed the other getters in simulant with the highest initial iodide content with distribution coefficient (K_d) values of 2.2×10^4 mL/g after 2 hours, which remained constant for at least 15 days. Similar results were observed in oxic conditions, but the tests were only run for 48 hours.

Argentite also performed reasonably well in anoxic conditions but was much slower, gradually absorbing the iodine until exhibiting a K_d of 1.8×10^3 mL/g after 15 days. The common zeolite substrate used in these materials is likely not stable in contact with LAW over long service times due to the high pH environment, which has been shown to release silver in LAW (Asmussen et al., 2016). This work shows that iodine can be sequestered from LAW in a quick exposure or "strike"; however, long-term service of zeolite-based media is uncertain. To be successful for a long-term service configuration, a more stable substrate for the Ag would be needed and demonstrated effective using actual LAW.

Off-site disposal of the secondary waste containing ^{129}I is assumed to be done via direct disposal in macro-encapsulated grout (PNNL-28545, *Development and Characterization of Cementitious Waste Forms for K. Immobilization of Granular Activated Carbon, Silver Mordenite, and HEPA Filter Media Solid Secondary Waste*). Other disposal technologies for zeolite-based media have been developed including densification to a durable waste form (Jubin et al., 2014; Matyáš et al., 2016), and other low temperature processes (SRNL-STI-2017-00508, *Examples of Disposition Alternatives for Solid Secondary Waste*). The immobilization and disposal of iodine sorbents and resulting waste forms is an active area of research within DOE Office of Nuclear Energy programs. Vitrification of the spent media in either the HLW or LAW melter is not likely to be required and such an approach is at a low TRL. Since the spent, iodine-loaded media selected for use would be expected to be chemically and physically stable during interim storage, the media could be stored while a final disposition path is determined. Both on-site and off-site disposal are feasible for the spent iodine media. The release behavior of both the iodine and silver need to be considered due to the RCRA designation of silver.

A closely related material, silver-loaded mordenite, has been shown compatible with a grout immobilization method to sequester the silver (Scheele et al., 2015) and shown to have enhanced iodine retention in leach testing of the grout waste form (PNNL-30105, *Iodine Speciation Basis and Gap Analysis for Hanford Tank Farm Inventory and During Processing*; PNNL-28545). Further discussion of iodine and possible immobilization of spent media is provided in Volume II, Appendix E, Section E.3.1.1.

An example media is a silver-exchanged zeolite and other similar commercially available materials (e.g., IONEX Ag400[25]). The silver-based media pretreatment approach has demonstrated iodide removal from simulated LAW in batch tests on the bench scale (Asmussen et al., 2016). The iodine removal and media immobilization technology are at low TRLs.

Removing iodine from the LAW stream would decrease the iodine inventory in the primary grouted LAW waste form in the IDF. The envisioned silver-impregnated zeolite would presumably be very stable during storage and have minimal leachability to the environment because of the extremely low solubility of silver iodide in water (PNNL-28545, Li et al., 2019). Removing iodine, instead of using a selective additive (getter) to the supplemental LAW waste form, would minimize adverse impacts of silver (a hazardous metal) in a grout waste form. A specific waste form for the iodine-containing spent media is assumed to be developed that is environmentally stable and compliant with off-site disposal requirements. However, there are numerous challenges with implementation of the technology. Silver carries both a high cost and a RCRA designation. Further, the chemistry of iodine in LAW is not understood (PNNL-30105) and may exist in multiple chemical forms in solution, such as iodate ion (IO_3^-) which would have lower affinity for Ag-containing media. The chemical behavior and speciation among the various waste compositions, along with removal and sequestration methods for the different species, would need significant research.

Alternatives Grout 1C and 2C assume iodine removal is required for on-site disposal. To implement that process, research and development will be required to develop and mature the technology needed. More detail on alternatives for iodine sequestration and/or removal are available (SRNL-STI-2020-00228). Laboratory testing has been performed with other technologies, which are considered less mature and/or less effective than the silver-zeolite material.

Table C-7 summarizes the status of iodine removal technology.

Table C-7. Iodine Removal Technology

Knowns	Unknowns
• Demonstrated rapid 99+% removal of iodide with simulant wastes with Ag-zeolite • Multiple potential immobilization pathways for spent iodine-loaded zeolite media	• Speciation of iodine in tank waste liquids and sorption properties of different forms • Demonstration of iodine removal with actual waste • Ag-zeolite media chemical stability • Determination of final waste form • Spent media characterization • Column/CSTR performance • Media production at scale • Sorption kinetics in column or CSTR design • Leachability of silver into tank waste liquid • Interfering waste components (e.g., Cl^-) • Effect of complexants on silver stability

CSTR = continuous stirred tank reactor.

[25] IONEX is a trademark of Molecular Products, Inc., Louisville, Colorado.

C.15.3 Alternative Grout 1D: Single Grout Plant with Sample-and-Send for Technetium/Iodine Diversion and Grout 2D: Separate Grout Plants for 200 East and West Areas with Sample-and-Send for Technetium/Iodine Diversion

For alternatives Grout 1D and 2D, similar to other alternatives, the waste is sampled and analyzed prior to processing. The analysis results for ^{99}Tc and ^{129}I concentrations are used to decide if the grouted waste form is disposed of onsite or sent offsite. After TFPT treatment, the waste is grouted into containers that are disposed of either onsite or offsite. Those with a ^{99}Tc and ^{129}I content below a threshold value are sent to IDF, and those above the threshold amount for either ^{99}Tc or ^{129}I are sent to an off-site disposal facility. The threshold limit has not yet been defined, but would be tied to the risk budget tool used in the PA. Below are descriptions of the concept. The subsequent TFPT, LDR, and immobilization steps for Grout 1D and 2D are discussed in the descriptions for Grout 1A and Grout 2A, respectively.

Sampling and Disposal Selection

Figure C-22 shows the molar concentrations of ^{99}Tc, ^{129}I, and ^{79}Se projected to be in the feed vector during supplemental LAW treatment as calculated for the most recent Hanford System Plan (ORP-11242, Rev. 9). The molar concentration, shown in the figure, is in the range of 6.0E-5 to 1.2E-4 M for ^{99}Tc and 2E-6 to 7E-6 M for ^{129}I during the first 7 years of LAW supplemental treatment and processing but drops to about one-third that range to 2E-5 to 6E-5 M for ^{99}Tc and 1 to 2 E-6 M for ^{129}I for the remaining years. This suggests that the quantity of ^{99}Tc and ^{129}I that remains onsite could be reduced by off-site disposal of the treated LAW produced during the first several years, with the remaining waste disposed of onsite. Figure C-22 also shows that the ^{79}Se content is low throughout the mission and is therefore not included as a deciding factor in on-site or off-site disposal.

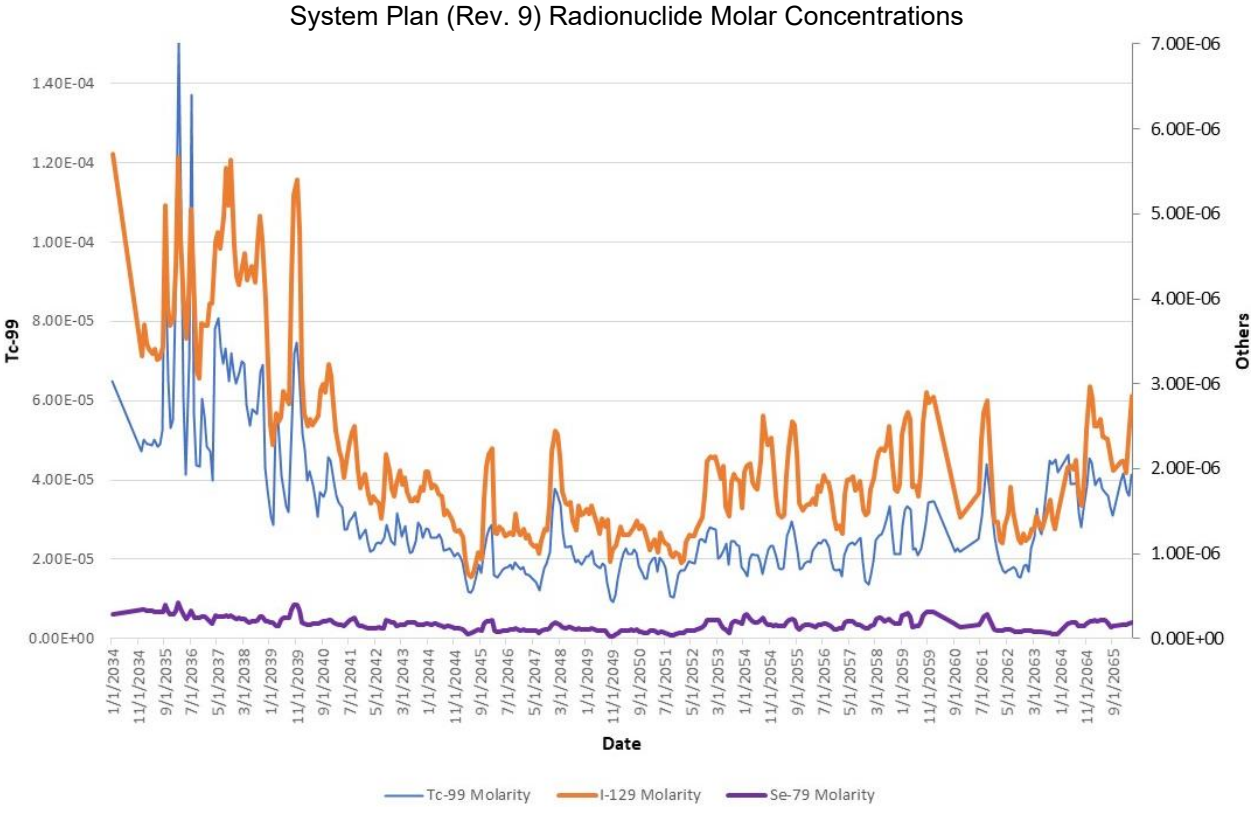


Figure C-22. ^{99}Tc, ^{129}I, and ^{79}Se Concentrations for Supplemental Low-Activity Waste Processing

The data used for the System Plan (ORP-11242, Rev. 9) feed vector for supplemental LAW treatment were used to calculate the potential benefit of this approach. If 50% of the waste batches that contained the highest technetium was shipped offsite, the amount of technetium that remained onsite from supplemental LAW treatment and processing (only) would decrease by 69%. Calculating a corresponding ratio for iodine is not practical because a sizeable but uncertain and probably varying fraction of iodine vaporizes in the melter and is captured in secondary offgas streams or components, which are disposed of onsite. However, this strategy could be used to decrease the inventory remaining onsite.

For alternative Grout 2D, which is essentially a combination of Grout 2A and 2B, where a decision point is inserted to dispose of the treated LAW onsite or offsite is based on the technetium and iodine content. Any benefits of the sample-and-send approach will be identified in the evaluation of alternative Grout 1D. The evaluation of those three alternatives will encompass the advantages and disadvantages of alternative Grout 2D. Because these alternatives are fully evaluated independently, no further evaluation of Grout 2D as a separate alternative is warranted. Any advantages identified in evaluating Grout 1D, 2A, and 2B will be compared to the those in evaluation of Grout 1D and will allow a determination if Grout 2D would be a further improvement without a full evaluation.

C.16 ALTERNATIVE: GROUT 6, PHASED OFF-SITE AND ON-SITE GROUTING IN CONTAINERS

Although there are several potential hybrid alternatives, the one envisioned to be the fastest at treating waste and thus the most reduction of risk regarding removal of waste and minimizing further tank degradation was the only one fully evaluated. Alternative Grout 6 is the example hybrid that was found to dominate the hybrid alternatives and is described below.

This hybrid alternative begins with one process implemented in phases by grouting waste offsite, and then onsite, with off-site disposal and then transitions to a final process of on-site grout production and disposal. This hybrid alternative gives time to develop the waste form performance information and PA modeling needed to complete remaining technology maturation to support the final phase of on-site disposal (e.g., characterizing waste, grout formulations/additives), while simultaneously making progress and working within the budget for the third phase to begin. In the interim, the configuration of the on-site disposal can be selected and any getters or radionuclide removal technology can be matured while still making progress using off-site treatment and disposal. The eventual transition to on-site production and disposal is expected to lower the overall mission cost and therefore maintains the lowest overall mission duration and risk. Of course, the on-site production and disposal alternative could instead be initiated immediately, avoiding off-site production and disposal. However, this approach is not the fastest at reducing risk of tank leaks, in part because it is reliant on the timing for approvals and the federal budget cycle, followed by grout plant construction time. If the off-site production and disposal is deemed infeasible due to unforeseen issues, the early construction and startup of the most favorable on-site alternative would be able to gain at least some advantage of the early removal of liquid waste from the tanks. A modular grout production system could potentially be co-located along with planned waste retrieval infrastructure in some tank farms, but would require further evaluation, as this alternative was not envisioned to be the most cost-effective or fastest way to complete the entire LAW supplemental treatment mission. As described in Section C.12, the reasons are largely due to the need for constructing considerable infrastructure at multiple locations.

This conceptual hybrid alternative, shown in Figure C-23, is a phased approach that combines alternatives Grout 4B (off-site vendor, off-site disposal) in Phase 1 beginning in 2026 and aspects of Grout 2B (separate on-site pretreatment plants with off-site grouting and disposal) and Phase 2 (adds on-site grout production in 200 East Area) in phased startup in 2034-2035, and transitions to Phase 3 with an on-site grouting and disposal method in 2040.

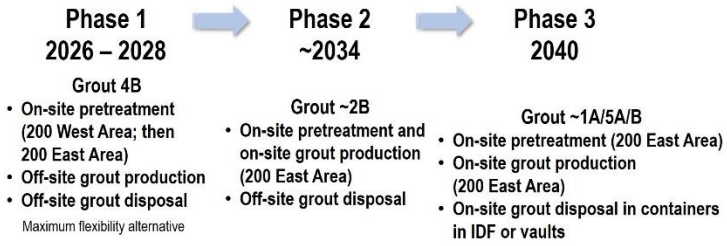


Figure C-23. Alternative Grout 6 Concept

The configuration of the on-site disposal (e.g., containers in vault, alternative Grout 5B) and any getters or removal technology needed can be developed in the interim while the off-site treatment and disposal is underway, along with further PA modeling. The purpose of this alternative is to expedite retrieval and disposal of wastes within site budgetary limits. The waste is initially pretreated in 200 West Area in a TFPT system undergoes LDR treatment (if needed), and the liquid is then shipped to an off-site immobilization vendor and the grouted waste form is disposed offsite (comparable to alternative Grout 4B). Multiple vendors are currently available that have the technical ability to grout the waste, and one or more could be used for this service.

A TFTP and LDR treatment process would be constructed later in Phase 1 and operated in the 200 East Area, with the same off-site grouting, packaging, transportation, and disposal steps, similar to alternative Grout 4B. On-site grout production could commence in 200 East Area in Phase 2. This alternative gives time to develop the information and work within the budget for the third phase to begin with the 200 East Area plant performing both the TFPT treatment, LDR treatment, and on-site grouting plant that creates a waste form that is disposed of onsite, similar to alternative Grout 1A or Grout 5A/B. The exact configuration and operation of the on-site grout production and disposal system (i.e., Grout 1A or Grout 5A/B) would be determined in the interim period based on the outcome of PA modeling, technology development, and permitting activities before 2040. Whether the on-site disposal in Phase 3 is in containers in IDF (similar to alternative Grout 1A) or in a monolith or containers in a vault (similar to alternatives Grout 5A or 5B) would also be decided based on these outcomes. Alternative Grout 5B was assumed for costing in this phase, since this alternative is expected to be the most expensive of these three alternatives. Grout 1A was used for the technical evaluation because it is expected to have the lowest technical certainty, in part due to the need for getter development. Ultimately, if on-site grout disposal is found not viable, the fallback option would be to dispose of all of the waste offsite.

Since the off-site contractor is handling both immobilization and disposal, the contractor would choose both the immobilization technique and the final packaging size and type and secondary waste disposal, per common commercial practice. For this study, grout is assumed for costing purposes. Construction of the TFPT, LDR treatment, and a load-out station onsite would be needed, along with permitting for processing and disposal and ultimately, on-site disposal. Figure C-18 (Section C.13) (with off-site disposition) provides a schematic representation of this portion of the alternative.

This alternative assumes off-site supplemental LAW treatment operations through the final years of DFLAW operations and in support of HLW vitrification startup. During the start-up and initial operations of HLW vitrification, an on-site grouting capacity will be developed and constructed in the 200 East Area. On-site grouting operations could commence in 2035–2039 and run in parallel with off-site grout until full capacity is realized, transitioning to on-site disposal in 2040. At this point, WTP LAW vitrification and on-site grout will suffice for balance of mission LAW feed immobilization.

Although not included in this evaluation, if needed depending on the pace of the 200 West Area saltcake-rich SST retrievals, an additional grouting plant could be constructed near the SY Farm. Figure C-19 (Section C.14) (with on-site disposition of containerized grout in IDF), provides a schematic representation of this portion of the alternative, which is comparable to alternative Grout 2A. The evaluation of this alternative assumes that the iodine getter is included in the grout formulation for the final phase, with on-site container disposal in IDF. However, the work in the interim period may identify that technetium and iodine removal or disposing as containers in vault (without getters) for on-site disposal is optimal. The cost estimate will use the disposal in a GDU vault to bound the estimate, but the technical evaluation is for using the getter with on-site disposal in IDF due to lower technical certainty for getter development.

This alternative assumes that the grouted waste form will be packaged in a similar manner as alternative Grout 1A (8.4 m^3 polypropylene bags inside a reusable steel box that can be disassembled). Both on-site and off-site treated waste will use these packages as the transportable form. On-site disposition is assumed to be in IDF. For the cost estimate, four GDUs will be assumed – ultimately the number of GDUs depends on total treated LAW volume, start date, and duration of on-site disposition.

Early start of LAW processing, particularly in the 200 East Area, alleviates DST space limitations and allows for HLW vitrification support as required for caustic dissolution of aluminum and sludge washing. These support operations will generate LAW feed; the program will be required to process significantly more volume. This additional volume may increase the total LAW feed volume for disposition from nominally 100 to 137 Mgal.

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Appendix D. Selection Criteria Assessments for Each Alternative

D.1 INTRODUCTION

The decision-informing criteria described in Volume I, Appendix A were developed as assessment measures for the alternatives evaluated in this report. Each alternative was assessed against the criteria by a sub-team of subject matter experts on the Federally Funded Research and Development Center (FFRDC) team. Where applicable, this expert team reviewed previously developed technical reports to identify information to support each assessment. In the absence of specific technical information regarding specific criteria, expert judgement from related work and experience was used to inform the assessment.

D.2 SELECTION CRITERIA ASSESSMENTS

Each of the criteria for each alternative were reviewed by the team, and the results were documented. The detailed results are included in this appendix for each of the 15 alternatives that were fully evaluated.

D.2.1 Selection Criteria Assessment for Alternative Vitrification 1

Alternative Vitrification 1:

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. ***Residual threat to health and environment upon successful completion***

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents – all retained – amount increased by treatment.]

1.1.1.1. Nitrates/nitrites – Low residual toxicity. Nitrate/nitrite are nearly completely destroyed by vitrification and offgas processes – small residuals in caustic scrub solution that is sent to the Effluent Treatment Facility (ETF) and end up grouted for disposal in the Integrated Disposal Facility (IDF).

1.1.1.2. RCRA metals – High residual toxicity. RCRA metals are contained in the primary waste form except mercury. Final partitioning of mercury has high uncertainty. All primary offgas components will have mercury contamination and secondary offgas components will have mercury contamination up to the granular activated carbon (GAC). Mercury captured on the GAC will be micro-encapsulated in grout. Some mercury will partition to the Liquid Effluent Retention Facility (LERF)/ETF and end up in a grouted waste form disposed of in IDF. No destruction; mercury is vaporized to secondary stream.

1.1.1.3. Land Disposal Restrictions (LDR) organics – Low Residual toxicity. Most organics are destroyed by the vitrification and secondary offgas processes. Some organics generated by incomplete combustion of sugar would be captured in the submerged bed scrubber (SBS) condensate and partitioned to LERF/ETF for destruction. Some organics will be captured by the GAC and grouted for disposal in IDF. Organics in waste largely destroyed, whereas melter produces some; remaining organics partition to secondary waste and are destroyed or sequestered in subsequent treatment; if planned disposition is found inadequate, it is assumed that changes would be made to processes to be within regulatory requirements.

1.1.1.4. Ammonia – High residual toxicity. The vitrification process generates ammonia that will be partitioned to the LERF/ETF for treatment. In addition, ammonia is added to the secondary offgas system (to destroy NO_x) and emitted from the vitrification facility stack. Ammonia in ETF will be precipitated and incorporated into a grout waste form disposed of in IDF with unknown long-term behavior.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides
[MOE: Estimated peak groundwater concentration at IDF Performance Assessment (PA) compliance point over ~1,000 years (to DOE O 435.1, *Radioactive Waste Management*; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period) (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*).

1.1.2.1.1. Iodine – Iodine is expected to partition predominately to solid and liquid secondary wastes (liquid/solid/gas). Release rates for some macroencapsulated components (solid secondary waste, e.g., GAC) expected to be higher than microencapsulation of iodine in liquid secondary waste grout from ETF; both are disposed of in IDF (without getters) but improvements to primary waste form could be applied to secondary wastes.

1.1.2.1.2. Technetium (non-pertechnetate is evaluated in Section 1.2.2.2) – Most (~99%) ^{99}Tc assumed to be retained in the primary waste form – and 2017 IDF PA predicted low-activity waste (LAW) glass contribution to be 10× lower than compliance limit. A small fraction will be captured on the high-efficiency particulate air (HEPA) filters, which are crushed and macroencapsulated in grout. Leach rates from the spent HEPAs is evaluated in the current PA but predicted quantities of technetium on HEPA filters are assumed to be extremely low but do not accurately account for system full performance.

1.1.2.1.3. Selenium-79 (^{79}Se) – Uncertainty in partitioning due to volatility. Like ^{99}Tc, a small portion could be captured on the spent HEPA filters that are microencapsulated and disposed of in IDF. Low inventory of ^{79}Se (114 Ci, see Volume II, Section E.3.1.3) leads to minimal risk to drinking water.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites. N/A – Destroyed in melter with small amount of nitrate produced and present in the ETF liquid secondary waste, and IDF PA risk budget tool showed peak concentrations 10× below on drinking water standards.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives.] – Ammonia is generated by the melter process (when sugar used as a reductant) and is also added during secondary offgas treatment to destroy NO_x. Ammonia from the melter process is typically partitioned to LERF/ETF while excess ammonia added during secondary offgas treatment is exhausted from the vitrification facility stack. Ammonia will also be present from first LAW melter system so its presence at ETF is not differentiating among alternatives. Ammonia in ETF is precipitated and encapsulated in grout waste form disposed of in IDF. Release from waste form at some TBD rate either during production, curing, or disposal is likely.

1.1.2.4. RCRA metals – [MOE is leachate Toxicity Characteristic Leaching Procedure (TCLP) compliance.] Leach rates of RCRA metals from the glass are predicted to be very low and expected to pass TCLP.

1.1.2.4.1. Mercury – [MOE is retention of mercury in primary vs. secondary waste form.] Mercury will not be retained in glass and will end up in a grouted waste form for all options. For vitrification, the mercury will be portioned throughout the secondary wastes, with most presumed to be on the activated carbon bed.

1.1.2.4.2. Chromium – [MOE is retention of chromium in waste form.] Chromium will be captured in the primary waste form and leach rate dependent on the dissolution rate of the glass. Like technetium, a small fraction could be partitioned to the spent HEPA filters that are macroencapsulated in grout and disposed of in IDF.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals (e.g., lead) appear not to exceed Drinking Water Standards (DWS) limits and are significantly beneath concentration of chromium.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – For 1 gallon of LAW feed: 0.34 gallons of primary waste glass, 0.05 gallons of spent equipment, 0.05 of grouted solids from ETF, and 1.8 gallons of liquid effluent disposed of at a state-approved land disposal site (SALDS). (Note: Flush volumes not included in water effluent totals) (RPP-RPT-63328, *Calculating the Non-Monetary Impact of Operating a Vitrification Facility*).

1.2. Long-term risks upon successful completion
[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Destruction of organics. High uncertainty exists in the speciation of the organics in the waste feed; the amount and speciation of organics that will be vaporized, destroyed, or produced by the melter and scrubbed from the offgas in the primary offgas system and subsequently sent to LERF/ETF; and the amount and type of organics that will be captured on the GAC, which is microencapsulated and disposed of in IDF.

1.2.1.2. Nitrates/nitrites – High confidence that nitrate and nitrite will be nearly completely destroyed by the immobilization process.

1.2.1.3. Ammonia/ammonium ion – Moderate risk. None in primary waste form. Ammonia in secondary liquid waste treated at LERF/ETF and will be in the immobilized waste form disposed of in IDF.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – Moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – Moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with regard to groundwater

1.2.2.1. Iodine – Moderate confidence overall. Low confidence that partitioning of iodine through process will proceed as expected and what resulting speciation will be. High confidence that the amount of iodine in secondary wastes will be higher than assumed in IDF PA. Partitioning significantly impacted if melter idles frequently. Any iodine retained in glass will have low leach rates dependent on glass stability. Low confidence in the immobilization of iodine in either stabilized solid secondary waste (e.g., GAC) or stabilized liquid secondary wastes assuming no getter used in secondary waste grout. Iodine is a key constituent of interest in the IDF PA. ^{129}I can define waste classification but concentrations in secondary wastes are lower than the U.S. Nuclear Regulatory Commission (NRC) low-level waste (LLW) Class A limit[1]. Once released by chemical reactions and leached into the subsurface there is limited to no natural attenuation of iodide, and as such the secondary waste iodine inventory could impact groundwater compliance limits. Mitigated during the compliance period by low rate of water to transport.

1.2.2.2. Technetium (including non-pertechnetates) – Moderate confidence overall. High confidence that partitioning of technetium through process will proceed as expected, including non-pertechnetate (converts to pertechnetate in melter). (Note: It is also expected that the amount of ^{99}Tc in secondary wastes will be higher than assumed in IDF PA due to model simplifications that did not incorporate all known impacts on ^{99}Tc partitioning.) Partitioning to offgas is significantly impacted if melter idles frequently or wet electrostatic precipitator (WESP) deluge frequency/time is higher than expected or if its scrubbing efficiency is lower than expected. Any ^{99}Tc in the primary glass waste form will have leach rate dictated by stability of the glass. Within the grouted secondary waste form, there is high confidence that technetium will be reduced and insoluble technetium. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form can be destabilized with time due to oxidation but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA.

[1] ^{129}I is listed in Table 1 of 10 CFR 61.55 *Waste Classification*, that is used to classify wastes for near-surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

Technetium can define waste classification and concentrations may approach the Class A limit[2]. Once in the subsurface, there is limited to no natural attenuation of technetium, and as such the secondary waste grout technetium inventory could impact groundwater compliance limit.

1.2.2.3. ^{79}Se – High confidence in minimal risk. Limited to no data to date on the partitioning in Waste Treatment and Immobilization Plant (WTP) and mobility within grout waste forms. ^{79}Se is a RCRA metal (as selenium) but only a small inventory across the Hanford tanks (2 kg) may reach the secondary waste. Selenium has limited attenuation in the Hanford subsurface. The limited inventory may minimize overall risk to groundwater. Mitigated during the compliance period by minimal water infiltration thru vadose zone.

1.2.2.4. Nitrates/nitrites – High confidence that nitrate/nitrite will not impact groundwater due to destruction during process and added nitrate/nitrite had limited impact in the 2017 IDF PA from secondary wastes.

1.2.2.5. Ammonia/ammonium ion – Moderate confidence overall. Liquid secondary waste streams will contain significant ammonium that can be converted to ammonia in alkaline condition. Use of an ammonia tolerant grout can limit ammonia release in processes but long-term stability unknown. From the waste form, ammonia can both evaporate as vapor and leach to soil. Mitigated during the compliance period by low amount of water infiltration.

1.2.2.6. RCRA metals – High confidence that RCRA metals (except mercury) will be effectively immobilized in a primary waste form with low leach rates. Mercury is partitioned entirely to secondary waste streams.

1.2.2.6.1. Mercury low confidence in overall fate – Mercury to partition to GAC where it will be stabilized/macroencapsulated as solid secondary waste. High confidence in ability to pass TCLP using slag in grout formulation with a high confidence in ability to sequester due to mercury sulfide formation. High confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface. Expect to be absorbed primarily in sulfur-impregnated carbon bed; but will be widely distributed in the offgas system and some to LERF/ETF; mercury leaching from carbon bed has been tested but not elsewhere in the system.

1.2.2.6.2. Chromium – High confidence in expected retention in glass waste form, refractory, and bubblers with low leach rates from glass dictated by stability of the glass.

1.2.2.6.3. Other RCRA metals – High confidence that other RCRA metals are expected to be in glass waste form and expected to leach at rate dictated by the durability of the primary glass waste form.

[2] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

1.2.3. Confidence in total volume of primary and secondary waste forms produced
Overall moderate confidence. High confidence in volume reduction of primary waste form. Medium confidence in amount of secondary waste generated – if total operating efficiency (TOE) is lower than projected, it would lead to higher secondary waste volume per liter of feed, which would lead to larger amounts disposed of in IDF.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk.
[MOE is time to start and processing duration risk of tank leaks for both double-shell tanks (DST) and single-shell tanks (SST) is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.2 for more detail). Startup in ~25 years, 3-year ramp up to full processing rate, low flexibility in processing rate, moderate throughput/TOE, complex and unique components, high maintenance needs, and large secondary waste handling needs increases risk of delays and therefore increases risk of additional leaks. Startup of this process in ~25 years has high risk of additional tank leaks because retrievals would be delayed vs. the schedule to support high-level waste (HLW), increasing time available for corrosion-induced leaks due to ongoing tank degradation.

Continuity of operations after startup – loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Because this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative consumes the entire initial benchmark supplemental LAW treatment budget, providing no opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is no potential for reducing risk of leaks.

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety
[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Multiple hazards. The high temperature process results in volatilization of selected radionuclides, increasing the risk for worker exposure. In addition, the buildup of radionuclides (^{99}Tc, ^{137}Cs, ^{129}I, others) in the recycle flywheel between the melter, offgas, and evaporator systems increases the exposure risk. The size and scope of the operations increase the number of workers exposed during normal operations and the extensive use of consumables (e.g., bubblers, melters, HEPA filters, GAC) require frequent exposure of these workers to hands-on maintenance activities with potential direct exposure to the radioactive material. Construction would be near operating radioactive facilities and ground contamination (i.e., contamination risk due to high vapor concentration due to flywheel, secondary waste handling, and extensive maintenance).

2.2.1.2. Chemical exposure – Multiple hazards. Similar to radiation exposure, the high temperature process results in volatilization of selected chemical species of concern and the generation of toxic offgas, increasing the risk for worker exposure.

In addition, the buildup of species (e.g., mercury) in the recycle flywheel increases the exposure risk. The size and scope of the operations increase the number of workers exposed during normal operations and the extensive use of consumables (e.g., bubblers, melters, HEPA filters, GAC) require frequent exposure of these workers to hands-on maintenance activities with unavoidable direct exposure to the chemical species. Furthermore, the use of hazardous chemicals (e.g., NaOH, anhydrous ammonia) in the process add to the hazards faced by workers. (38 high hazard consequences [RPP-RPT-63328].)

2.2.1.3. Particulate exposure – Few hazards that are not easily mitigated. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates. Mitigated by common commercial practices.

2.2.1.4. Physical injury – Moderate hazards. The large number of maintenance and other activities required for the vitrification process increase the exposure of hands-on workers to industrial hazards. 38 high hazards conditions were noted by Washington River Protection Solutions, LLC (WRPS) for vitrification of LAW (due to large number of maintenance activities) (RPP-RPT-63328).

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments of rad/hazardous shipments to high number of rad/hazardous shipments.)] – Low risk. The vitrification alternative generates the lowest waste volume amongst alternatives, and it is expected that all waste is disposed of in the IDF leading to the lowest possible transportation risk. Transport of hazardous chemicals (NaOH, anhydrous ammonia) to the site represents an exposure risk due to accidents.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] (High discharge volumes; new ETF believed necessary.) – Water is not incorporated in the primary waste form and large volumes of water are added during the treatment process. The liquid effluents from the vitrification process require additional treatment prior to release, using the existing LERF/ETF or a new, similar facility. A large fraction of the ^{129}I from the waste feed is expected to be in the liquid secondary waste and could result in an additional waste stream if the ^{129}I must be removed prior to sending the effluent to LERF/ETF. Approximately 2-3 gallons of treated wastewater will be sent to SALDS for each gallon of supplemental LAW feed. Tritium is all released to the environment [SALDS] immediately.

2.3.2. Atmospheric discharges

[MOE: Fraction of radionuclides and contaminants of concern (CoC) converted to vapor in offgas system.] – Expect 34 MT NH_3 and 4 MT "other" per 1 Mgal feed; 0.006 mrem ^{14}C discharge (RPP-RPT-63328); potential for ^{129}I.

2.3.3. Transfer/process tank (on-site) spills
[Unplanned discharges MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category.)] (Low – only risk is transfers to LERF or Effluent Management Facility [EMF].) – The large number of unit operations and high temperature operations, the corrosive nature of the recycle stream generated, and the use of corrosive chemicals increase the chances for on-site spills during treatment compared to other options (but all transfer lines have secondary containment).

2.3.4. Off-site transportation spills
[MOE: No risk of off-site spills to high risk for off-site spills.] – Low risk. No shipments of liquid and no off-site immobilized waste. Off-site transportation risks include delivery of chemicals, including liquids such as sodium hydroxide and anhydrous ammonia, diesel fuel, and other industrial chemicals and glass-forming chemicals (GFC)/minerals.

2.3.5. Secondary waste streams generated
[MOE: Volume of waste (liquid and solids and equipment); low quantity of secondary waste to highest quantity of liquids, solids, and equipment.] – Very high volumes. Millions of gallons of liquid secondary waste are generated annually, leading to the requirement for additional treatment capacity at the LERF/ETF. In addition, the short operating life of components of the vitrification process (e.g., melters, bubblers) and the large number of consumables (e.g., HEPA filters, GAC media) lead to large volumes of solid secondary waste. The waste streams will likely contain significant portions of the ^{129}I, all the mercury, and some of each of the other CoCs in the waste feed. Spent melters are placed in containers and disposed of in IDF. Melters have an estimated operational lifetime of five years.

2.3.6. Greenhouse gas emissions (see Section 2.3.2 above) – At a minimum, treatment of 1.0E6 gallons of waste consumes 1,500,000 gallons (4,800 MT) of diesel fuel (~15,000 MT as CO_2), 168 MT sugar, 283 MT soda ash (sodium carbonate), 295 MT lithium carbonate (total of ~550 MT as CO_2), 74 GWh of electricity, and requires approximately 570 deliveries of fuel oil, glass formers, and other process chemicals (based on information from RPP-RPT-63328, and DOE/RL-2022-33, *Hanford Energy Emissions 2022-2037 – Reducing the Gap to Net Zero*[3]).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) – The existing WTP LAW Vitrification Facility required approximately 20 years to complete. A supplemental LAW vitrification facility is expected to be at least twice as large as the WTP LAW Vitrification Facility and should be expected to take at least as long to construct. However, some efficiencies in design and construction could occur since the design is expected to be similar to the existing WTP LAW Vitrification Facility. In the benchmark funding scenario, the cost of the vitrification facility would extend the required schedule and would likely preclude completion of the facility in the time required. Hot start-up (CD-4) in ~2050 (see Volume II, Appendix F).

2.4.2. Duration to full capacity (additional years) – The facility would need to ramp up to full production in a short period of time (6 months) to support HLW processing. However, startup of similar facilities indicate that is more probable that a supplemental LAW facility would require 3 years to ramp up to full operations.

[3] Fuel oil and deliveries amount adjusted for annual consumption in DOE/RL-2022-33 vs. 1M gal of waste in 154 days per RPP-RPT-63328.

2.4.3. Duration of operations (additional years) – The facility would operate until the end of the entire HLW campaign. HLW campaign will begin later because the supplemental LAW treatment starts later. Additional delay to supplemental LAW treatment startup extends duration that existing equipment and first LAW melters must operate, exacerbating maintenance needs and requiring replacement of equipment and facilities that exceed their design life.

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues – Moderate risk that technical issues could delay startup. Expect first LAW to inform supplemental LAW melter design and operation, along with lessons learned from the Defense Waste Processing Facility and West Valley melters and pilot testing at Catholic University of America. Uncertainty exists in radionuclide partitioning and behavior across all waste compositions, production of LDR organics, along with overall integrated system complexity and additional facilities needed (e.g., ETF). (Delays due to technical uncertainties contribute to increased cost risk and therefore the potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – Very high risk of delay. Complex system with high maintenance requirements, multiple melters with partially shared systems, long operating duration, high temperatures, extensive balance of facilities, can contribute to potential extension of supplemental LAW and HLW processing duration.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Tech failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste, i.e., failure mode likelihood and result – this should be customized for each alternative with each unique failure mode and consequence.) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] The vitrification alternative will use the same flowsheet and approach as the existing WTP LAW Vitrification Facility. Portions of the process have been extensively tested using pilot-scale systems, but selected unit operations have very limited or no testing (e.g., the GAC and caustic scrubber). Uncertainty remains in the partitioning of selected species, but the baseline process is considered robust and able to immobilize the waste sodium in a glass waste form.

3.1.1.1.1. Corrosion of offgas system causing frequent extensive repairs/replacement – Very low risk of failing to complete, despite high volatility and recycling of offgas condensate leads to rapid corrosion of offgas system components (where mercury has been absent from testing but not believed to cause dramatic impact; pilot-scale system could have differences). Consequence: Frequent shutdown and component replacement.

Mitigated by operation of the WTP LAW Vitrification Facility that will help guide material of construction for supplemental LAW treatment.

3.1.1.1.2. Fire in offgas system – Low risk of failure to complete, but there is potential for fire in carbon bed; supplemental LAW could have different offgas components (organics, NO_x) (where mercury has been absent from testing but not believed to be impactful; pilot-scale system could have differences). Monitoring of gases and temperature in GAC mitigates risk. Consequence: Extended duration shutdown; system redesign/rebuild. Extended delays. Mitigated by operation of the WTP LAW Vitrification Facility that would help guide process for supplemental LAW treatment.

3.1.1.1.3. Release of radioactive material (e.g., ^{129}I, ^{3}H) or mercury or NH_3 (above permit) to atmosphere – Risk is unexpected partitioning of species under melter and offgas system operating conditions but would be mitigated if release occurs, so very low risk of failure to complete (pilot-scale system could have differences). Consequence: extended duration shutdown, system redesign/rebuild. Extended delays. Mitigated by operation of the WTP LAW Vitrification Facility that would help guide design and operations for supplemental LAW treatment.

3.1.1.1.4. Ability to control WESP as it ages – Very low risk potential to make collection of technetium ineffective; risk is unexpected partitioning of species under melter and offgas system operating conditions (where pilot-scale system could have differences). Consequence: extended duration shutdown, system redesign/rebuild. Delays. Mitigated by operation of the WTP LAW Vitrification Facility that would help guide design and operations for supplemental LAW treatment; ability to wash technetium from HEPA filters or dispose of offsite.

3.1.1.1.5. Overall uncertainty of I partitioning – Iodine partitioning was tested, so low uncertainty remains, but problematic amounts could distribute to caustic scrubber solution bound for ETF. Consequence: excess partitioning to caustic scrubber requiring mitigation instead of sending to LERF/ETF. Mitigated by data from LAW melter operation.

3.1.1.2. Process complexity (flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Very high process complexity. Vitrification of the supplemental LAW feed requires a large number of integrated unit operations and incorporation of a significant and variable recycle stream into the feed process. The high temperature processing generates an offgas that both requires extensive treatment prior to release and worker protections to prevent exposure. The process contains many items that require routine hands-on maintenance or replacement. The large recycle and extensive treatment system represent an interdependent and complex system where not all interactions are well understood.

Note that if designed the same as the LAW melter system, a single unit operation failure in the system will shut down the melter (or multiple melters for the secondary offgas system or GFC preparation system). In addition, the short cycle times of many of the feed and condensate handling processes require rapid turnaround of sample analyses, expedited batching of GFC batches, and complicates handling of the large number of receipts needed to keep the GFC silos and other process chemical feed tanks filled unless the feed tanks for supplemental LAW treatment are sized using a different basis than the current WTP LAW Vitrification Facility (very high interconnectedness). Consequence: Challenging to run system, delayed processing, additional costs, missed milestones. Mitigated by LAW Vitrification Facility operation providing input to operation and design but very high operating cost per day.

3.1.1.2.1. Unit Operations (33 systems listed below)

- Feed preparation tasks
  - Receipt of feed and recycle
  - Melter feed preparation
  - GFC batching
  - GFC blending and transfer
  - Melter feed system
- Melter
  - Feed compositional controls (high complexity)
  - Bubbler system (moderate complexity)
  - Cooling water system for refractory panels
  - Cooling for electrodes
  - Air lifts for pouring
  - Power supplies and electrode (moderate complexity)
- Primary offgas
  - Film cooler
  - Submerged bed scrubber
  - Wet electrostatic precipitator or steam atomized scrubber (high complexity)
  - Condensate collection
- Secondary offgas
  - Heater
  - HEPA
  - Activated carbon bed (moderate complexity)
  - Heat exchanger
  - Heater
  - Thermal catalytic oxidizer
  - Selective catalytic reduction unit (moderate complexity)
  - Caustic scrubber (moderate complexity)
- Effluent Management
  - Melter offgas condensate receipt and pH adjustment
  - Evaporation (moderate complexity)
  - Evaporator condensate collection and transfer to LERF/ETF

  - Evaporator concentrate collection and return to feed preparation process
- Container handling line
  - Pour cave
  - Fill height verification and inert fill station
  - Lidding station
  - Container swabbing and decon station (moderate complexity)
  - Container load out station.

3.1.1.2.2. Accuracy of controls needed

- Sampling/measurements needed to control process – Very high complexity. Batch qualification is expected to give composition for GFCs, but the internal recycle of concentrated melter condensate must be factored into the process. Sampling of the batch feed on a campaign basis, samples of each batch of recycle concentrate, and confirmation of the melter feed blend is currently performed for WTP LAW Vitrification Facility operations. If the process is closely coupled with HLW operations, additional sampling will be needed to account for the feed variations from the HLW effluents. In addition, sampling of the primary offgas condensate prior to evaporation and of the EMF evaporator condensate is expected during campaign transitions and if upset conditions occur.

  Control of the melter feed process is more art than science as the amount of cold cap coverage must be inferred from secondary indications and the response of the system to changes can take several hours. The secondary indications included melter pool and plenum temperatures. Cold cap coverage is controlled using melter feed rates and melter bubbling rates.

  These parameters also impact the reactions that occur in the melter plenum space such as reactions of nitrate to nitrogen, nitrous and nitric oxides, and ammonia, and the amount of feed organic destruction and production of organics from sugar. Consequence: Delayed processing, complex interrelated systems, melter idling causing variability in recycle composition. Mitigated by experience with LAW melter operation.

- Modeling needed to control process – Very high complexity. The vitrification process is driven by compositional requirements to efficiently process in the plant and produce an acceptable glass with predictable properties. The glass composition models predict the glass viscosity, liquidus temperature, product consistency test (PCT) and vapor hydration test (VHT) response, solubility of key components (e.g., sulfur, chromium), and electrical conductivity. The model is also used to predict glass composition for reporting purposes. Uncertainty in sample analysis accuracy and models. Consequence: See items below. Mitigated by experience with LAW melter operation.
  - Failure modes for improper operation
    - Glass viscosity

    - Improper viscosity (low or high) can cause the pour stream to drip, leading to strands of solidified glass between the pour spout and container. The pour stream can be diverted by these strands and could miss the container. Pour cell cameras are installed to monitor the pouring operation.
- Improper composition
    - High sulfur – If excessive sulfate is fed to the melter (or insufficient sugar) a gall layer can form on the surface of the melter that could lead to early failure of the bubblers and/or melter.
    - High chromium – Could lead to formation of crystals in melter.
- Liquidus temperature
    - Crystal formation could be mild or severe depending on magnitude of error. A gross error leading to large amounts of crystal formation is not considered likely. A small amount of crystals from a minor error could likely be handled by the vitrification system, but it is possible for crystal formation to negatively impact the melt composition leading to changes in viscosity, conductivity, etc.
- Electrical Conductivity
    - As with liquidus temperature, large errors that would lead to major processing issues are not expected. Improper electrical conductivity would lead to issues with maintaining the melter at temperature.
- PCT and VHT
    - PCT and VHT responses are modeled with no feedback mechanism in place during processing if the models are inaccurate at predicting glass performance. It will not be known that the glass did not meet durability limits unless future testing indicates issues with the specific composition poured or excessive leach rates are noted from the disposal site. The likelihood of glass composition issues causing excessive leaching from the IDF is considered low.
- Container composition
    - The composition of the glass in the container uses a simple model for single-pass glass retention for each species in the feed to predict the composition of the poured glass. The model currently does not account for cold cap coverage, idling, or other processing conditions. Thus, the composition of semi-volatiles in the reported glass compositions is likely to have a high amount of uncertainty.

3.1.1.2.3. Commercially available/similar (of a type) to available/bespoke systems – High number of custom components. Portions of a supplemental LAW vitrification facility could use commercially available equipment (e.g., exhaust fans, mixers, pumps), most components are of similar type systems modified for the supplemental LAW treatment facility and some systems are complete bespoke (e.g., melters, film coolers). Consequence: need to redesign/rebuild, causing mission delays. Mitigation is to get business to make replacement; build in on-site shop; purchase extras.

3.1.1.2.4. Overall flowsheet integration complexity – The flowsheet for a vitrification facility for supplemental LAW is extremely complex. The recycle of offgas condensate to the front end creates variability in the feed, a large number of GFCs must be accurately added to achieve high waste loadings using complex models to determine the required amounts for each batch, the feed to the melter must be distributed across three zones, the cold cap coverage must be inferred from secondary indicators, and the offgas system consists of 12 separate unit operations. The condensate from the primary offgas system must be evaporated and recycled. Two separate liquid effluent streams are generated, along with several solid waste streams. Life expectancy of the melter bubblers is expected to be ~6 months, requiring frequent maintenance on the melters to be balanced with the operating schedule. Operating experience from WTP LAW Vitrification Facility will help with the supplemental LAW treatment facility design and operation. Consequence: Delayed processing, complex interrelated systems, melter idling causing variability in recycle composition. Mitigated by experience with LAW melter operation.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed) – Vitrification requires extensive utilities, including large demands for diesel fuel, cooling water, electricity, steam, and compressed air, and process chemicals such as anhydrous ammonia, sodium hydroxide, sugar, and 12 GFCs. Sample requirements necessitate an integrated analytical facility operating on a 24/7 schedule. Cross-site supernatant liquid transfer line is needed to support this alternative. Secondary waste generation and limited lag storage require treatment facilities for these streams to be available. Operating experience from WTP LAW Vitrification Facility will help with the supplemental LAW treatment facility design and operation. Consequence: Delayed processing, complex interrelated systems, melter idling causing variability in recycle composition. Mitigated by experience with LAW melter operation.

3.1.1.4. Required demolition/removal/modification
It is expected that siting will not require demolition or removal of existing facilities. No consequences.

3.1.1.5. Technology Maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – The vitrification alternative will use the same flowsheet and approach as the existing WTP LAW Vitrification Facility. Portions of the process have been extensively tested using pilot-scale systems. Uncertainty remains in the partitioning of selected species, but the baseline process is considered robust to be able to put the waste sodium into a glass waste form. WTP LAW processing of direct-feed low-activity waste (DFLAW) feed should reduce uncertainty in the partitioning of these species while the supplemental LAW treatment facility is built. Consequence: Delayed processing. Mitigated by experience with LAW melter operation.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – WTP LAW processing of DFLAW feed should reduce technical uncertainty while the supplemental LAW treatment facility is built. Consequence: Delayed processing. Mitigated by experience with LAW melter operation.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions
[High heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – The ability to adjust waste loading and GFC recipe will allow a supplemental LAW vitrification facility to handle a wide range of feeds. Predicted waste soda loading for LAW range from 3-4% up to 25% with most batches over 20%. Non-pertechnetate is not an issue for the vitrification process since any non-pertechnetate not retained by the glass will react to form pertechnetate in the melter offgas system. Consequence: Delayed processing. Mitigated by experience with LAW melter operation.

3.1.4. Ability to incorporate future advances
[MOE: Easily incorporated to impossible.] – The high capital cost and unique operations makes incorporation of future advances challenging. Consequence: high cost of changes.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW budget.] – The funding needs for a supplemental LAW vitrification facility will likely exceed the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – The peak funding needs for a supplemental LAW vitrification facility will likely greatly exceed the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – Vitrification facilities have limited ability to operate at lower rates than needed to maintain a cold-cap on the melter as operating with a small cold cap results in excessive losses of semi-volatiles to the offgas. Idling the melter at temperature to allow enough feed to accumulate to allow operation for a period of time with a full cold cap also results in high semi-volatile losses. A cold shut down requires the melter to be replaced. Given that multiple melters are required, it may be feasible to allow a portion of the melters to remain in extended idle during periods of reduced feed, but this option still uses significant resources and melter life is not extended by idling. The "SLAW feed vectors" have considerable variability in the amount to be treated each month. Sufficient lag storage to provide a constant feed to the supplemental LAW treatment facility is not feasible.

3.2.4. Expected work remaining at failure point

[MOE: failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; text to funding shortfall/timing; describe when it fails; MOE is consequence only.) – A supplemental LAW vitrification facility failure is assumed to be caused by lack of funding during construction. Consequence: Alternate technology/solution must be developed. Delayed mission, delayed start of supplemental LAW processing. It is unlikely that sufficient funds will be available to complete a vitrification facility by the project need date.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not complete and never starts up. Start of the supplemental LAW treatment mission is delayed. Worst case is to commit to vitrification option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is unlikely that sufficient funds will be available to complete a vitrification facility by the project need date.

3.3. Likelihood and consequences of failing to complete due to unavailability of key services and materials

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider)] – The refractory used for the melters and other components have a single U.S. vendor. One system, the carbon dioxide decontamination system, has already been removed as a result of the vendor going out of business (along with previously unresolved issues with asphyxiation hazards).

Analytical services for WTP are provided by an on-site laboratory; this laboratory may not be able to handle the sample load from supplemental LAW vitrification facility with multiple melters, depending on configuration and sample requirements. Consequence is switching to an available material/equipment, expand capability, etc.; potentially causing additional cost and delays. While some delays may occur, a supplemental LAW vitrification facility is sufficiently large that it is not likely that a provider would be unwilling to provide materials or specially engineered parts.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above (all costs are discounted at 3% rate).

Total: $12,700 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$7,608 M (includes commissioning costs)

Note – Evaporation assumed provided by mission as part of HLW feed preparation facility.

4.2. Operations costs

$5,092 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.2 Selection Criteria Assessment for Alternative FBSR 1A

Alternative FBSR 1A: Fluidized Bed Steam Reforming On-site (A) Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. ***Residual threat to health and environment upon successful completion***

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents – all retained – amount increased by treatment.]

1.1.1.1. Nitrates/nitrites – Low residual toxicity. Nitrate/nitrite are destroyed by fluidized bed steam reforming (FBSR) and in the offgas system, and are essentially nondetectable in the primary waste form, but the offgas still contains some NO_x gas species. Nitrates were destroyed to detection limit levels (0.002 wt%) in the mineralized product, and overall offgas NO_x destruction was measured at between 91-94%, exceeding the goal for the Hanford LAW and WTP secondary waste simulants tests. (RT-21-002, *Report for Treating Hanford LAW and WTP SW Simulants: Pilot Plant Mineralizing Flowsheet*). Trace amounts of nitrate in the primary waste form would be insignificant in the disposal environment.

1.1.1.2. RCRA metals – High residual toxicity. RCRA metals are contained in the primary waste form except for mercury. All mercury is presumed to evolve to the offgas. All primary offgas components will have mercury contamination and secondary offgas components will have mercury contamination up to the GAC. Mercury captured on the sulfur-impregnated GAC would be micro-encapsulated in grout. No destruction.

1.1.1.3. LDR organics – Low residual toxicity. Most organics are destroyed by the FBSR and secondary offgas process. Some organics may be generated by incomplete combustion of coal but would be destroyed in the thermal oxidizer (TO). Organics in waste largely destroyed to non-detectable levels in the primary waste form, remaining organics destroyed in offgas system to within regulatory limits. Leftover coal in primary waste form, but not believed to be an issue.

1.1.1.4. Ammonia – Very low residual toxicity. The FBSR process should destroy whatever ammonia is in the LAW and does not introduce ammonia into the system. Ammonia and related compounds are likely produced in the denitration and mineralizing reformer (DMR) but are expected to be destroyed in the TO. No ammonia for long term impact.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Selected findings from the ASTM C1285, *Standard Test Methods for Determining Chemical Durability of Nuclear, Hazardous, and Mixed Waste Glasses and Multiphase Glass Ceramics: The Product Consistency Test (PCT)*, short-term and long-term durability testing, single pass flow-through (SPFT) testing, and pressure unsaturated flow-through (PUF) testing of the FBSR granular waste form produced from bench-scale, pilot-scale and engineering-scale testing indicate that (1) ASTM C1285 (PCT) releases would be expected to be near or more likely well below 2 g/m^2 (target), which means short-term, static release is comparable to processable WTP glasses,[1] (2) SPFT test data for silicon from the Savannah River National Laboratory (SRNL) bench-scale reformer (BSR) with modified radioactive tank waste product are two orders of magnitude lower than the data for LAWA44 glass, and (3) PUF test data indicates that rhenium release (analog for technetium) from a multiphase FBSR sodium aluminosilicate granular product is an order of magnitude lower than ^{99}Tc release from LAW glass (LAW AN102) (SRNL-STI-2011-00387, *Fluidized Bed Steam Reformed Mineral Waste Form Performance Testing to Support Hanford Supplemental Low Activity Waste Immobilization Technology Selection*; SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reser*vation). Thus, the normalized dissolution rates of the FBSR granular product are within the ranges of normalized dissolution rates for borosilicate glasses with compositions within the processable compositions of Hanford's WTP (PNNL-14805, *Waste Form Release Data Package for the 2005 Integrated Disposal Facility Performance Assessment*; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063, *Chemical Composition and PCT Data for the Initial Set of Hanford Enhanced Waste Loading Glasses*; PNNL-28838, *Enhanced Hanford Low-Activity Waste Glass Property Data Development: Phase 2*).

1.1.2.1.1. Iodine (Iodine mobility to groundwater is limited during the first 1,000 years compliance period due to facility performance) – Iodine is expected to partition predominately to the granular product (SRNL-STI-2011-00387). Release rates for iodine are expected to be near or more likely well below the 2 g/m^2 target (ASTM C1285 [PCT]) for the FBSR granular product and monoliths (SRNL-STI-2011-00387).[1]

[1] Accounting for the surface roughness of the mineral granules indicates that the FBSR product leach rate would likely be two orders of magnitude lower than the 2 g/m^2 target and, when the surface roughness of the mineral granules is ignored, that the FBSR product has an equivalent leach rate to "vitreous waste forms" (SRNL-STI-2011-00387).

However, PCT alone on a pristine waste form is not necessarily indicative of long-term disposal (i.e., IDF) performance (e.g., without additional information on alteration phases, thermodynamic and rate law parameters, structural incorporation).

The previous comparative performance estimates based on PCT, SPFT, and PUF results for a single-vendor steam-reforming material (RPP-17675, *Risk Assessment Supporting the Decision on the Initial Selection of Supplemental ILAW Technologies*) that suggested "*[g]iven the uncertainties, the groundwater impacts [and thus the normalized dissolution rates] of SR [steam reforming] are comparable to those of WTP glass*" are uncertain (including structural incorporation of ^{99}Tc and ^{129}I inferred from leaching results and how thermodynamic and rate model parameters were estimated without uncertainty quantification) and can be considered optimistic estimates.[2]

To date, only rhenium has been shown to exist in sodalite cage resulting from steam reforming of Hanford LAW (Dickson et al., 2014; Mattigod et al., 2006; Dickson et al., 2015; Pierce et al., 2014). Rhenium can be a suitable surrogate for technetium, and it was inferred that technetium could also be incorporated into the sodalite cage of the FBSR product. No observation of iodine incorporation into the sodalite cage from the FBSR process has been made to date. Corrosion testing of FBSR granular products has shown apparent congruent releases of iodine and technetium/rhenium providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016). Furthermore, there is direct evidence of iodine incorporation into sodalite cages in studies focused on vapor-phase capture of iodine using sodalite materials (Maddrell et al., 2014; Sava et al., 2011), which suggests that iodine may also be structurally incorporated in the steam reforming granular product sodalite phase. Some iodine may be sorbed onto the GAC, quantity is uncertain.

[2] In RPP-17675, all ^{99}Tc was assumed to be in the nosean phase and other contaminants (including ^{129}I) were assumed to be released in proportion to the rate at which ^{99}Tc was released from the nosean phase. The sodalite phase (which is isostructural with nosean and considered the host phase for ^{99}Tc and ^{129}I in more recent steam reforming studies (SRNL-STI-2011-00387) was not considered in the Preliminary Risk Assessment. These inferences are further complicated by the possible solid solution with sodalite and nosean as end members that may be present in the granular product (SRNL-STI-2011-00387). Additional testing suggests that dilute, steady-state dissolution rates are consistent with earlier data; however, there remain questions to be resolved, including (1) the applicability of Transition State Theory to the multimineral phase granular steam reforming product and corresponding model uncertainty; (2) the estimation and uncertainty quantification of thermodynamic and rate model parameters (e.g., activation energy, log K) other than the intrinsic rate needed for long-term performance prediction, especially for any solid solutions formed; (3) the locations of ^{99}Tc and ^{129}I based on solid phase measurements to confirm the hypotheses (i.e., structural incorporation in the sodalite cage) inferred from leaching results; (4) the rate of re-oxidation of the granular product during disposal (allowing release of ^{99}Tc not in the sodalite cage); etc.

1.1.2.1.2. Technetium (Non-pertechnetate was evaluated in Section 1.2.2.2; technetium mobility to groundwater is limited during the first 1,000 years [compliance period] due to facility performance) – Most (~99%) ^{99}Tc will be retained in the primary granular waste form, which exhibits very low leach rates either from structural incorporation in sodalite or the reduced nature of the granular product (SRNL-STI-2011-00387).[3] The release rates would likely be within those for borosilicate glasses with compositions within the processable compositions of Hanford's WTP (PNNL-14805; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063; PNNL-28838), but dependent on partitioning, structural incorporation,[2] and reoxidation of the waste form during disposal. To date, only rhenium has been shown to exist in the sodalite cage resulting from steam reforming of Hanford LAW (Dickson et al., 2014; Mattigod et al., 2006; Dickson et al., 2015). Rhenium can be a suitable surrogate for technetium, and it was inferred that technetium could also be incorporated into the sodalite cage of the FBSR product. Corrosion testing of FBSR granular products has shown apparent congruent releases of iodine and technetium/rhenium, providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016). A small fraction will be captured on the HEPA filters, which are crushed and macroencapsulated in grout. Leach rates from the spent HEPA filters are evaluated in the current PA, but the inventory to be disposed of is TBD. Expect about same amount on HEPA filters as in vitrification. Better single-pass retention of technetium in primary waste form vs. vitrification, leading to less technetium in offgas/HEPA filters.

1.1.2.1.3. Selenium-79 (^{79}Se) – Assumed to partition like sulfur, with most ending up in the primary waste form with very low leach rates. Like ^{99}Tc, a small portion could be captured on the spent HEPA filters that are macroencapsulated and disposed of in IDF. Expect about same amount on HEPA filters as in vitrification. Minimal impact due to limited quantity; 114 Ci total in the Hanford tank farms (per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*, see Volume II, Section E.3.1.3). Assuming high mobility from waste form release to subsurface is many orders of magnitude below conservative DWS.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

[3] X-ray absorption spectroscopy (XAS) data on technetium indicates that the +7 oxidation state in the sodalite cage is between 65-79% in the reduction-oxidation (REDOX) range of the FBSR operation with remainder as +4 in TcO_2 oxide and/or $Tc_2S(S_3)_2$. During durability testing, including long-term testing, there was no change in durability with sample REDOX, indicating that the +7 fraction of the technetium is insoluble in the sodalite cage, while the +4 fraction of the technetium is insoluble in the oxide and/or sulfide form (SRNL-STI-2011-00387).

1.1.2.2. Nitrates/nitrites [MOE: Estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – N/A, destroyed in DMR.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives.] – Ammonia in tank waste is destroyed in the FBSR process. DMR may produce ammonia but will be destroyed in the TO and not present in solid waste form.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Leach rates of RCRA metals from the granular waste are expected to be very low either from the nature of the granular product or low inventory in the LAW feed (SRNL-STI-2011-00387).[4] Only exceedances of TCLP Universal Treatment Standards (UTS) limits to date were for elements intentionally spiked above realistic limits.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Mercury will not be retained in granular product and will end up in the activated carbon waste form, which is assumed to be encapsulated in grout. Expect geopolymer waste form and encapsulated GAC grout to pass TCLP.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form.] – Chromium will be captured in the primary waste form with very low TCLP leach rates, although additional iron oxide catalyst (IOC) may be required where this material is also used as a denitration aid in the FBSR process (SRNL-STI-2011-00387). Like technetium, a small fraction could be partitioned to the spent HEPA filters that are macroencapsulated in grout and disposed of in IDF. Expect geopolymer waste form to also pass TCLP.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals is not known but expected to pass TCLP (SRNL-STI-2011-00387). Some TCLP leaching values for antimony and cadmium exceeded UTS limits; however, these values were shimmed in the feed (without regard for TCLP) to allow quantitative evaluation of mass balance/offgas results. High confidence in small inventory of cadmium (where inventory is not recorded in the Best Basis Inventory [BBI] [2018]) because only small quantities of these chemicals are present in the waste and analytical data are limited (HNF-SD-WM-TI-740, *Standard Inventories of Chemicals and Radionuclides in Hanford Site Tank Wastes*). Only ^{125}Sb is recorded in the BBI because only small quantities of the other antimony isotopes are likely present in the waste. The total activity of ^{125}Sb (~615 Ci) as of 2018 translated to less than 0.5 gram in all Hanford tank wastes.

[4] TCLP analyses for most of the RCRA metals were well below corresponding UTS (40 CFR 268.48, "Universal Treatment Standards," Non-wastewater) (SRNL-STI-2011-00387). However, some TCLP analyses for antimony, cadmium, and chromium exceeded UTS limits depending on the laboratory performing the analyses. After additional evaluation (including inventory considerations for cadmium and antimony), only the chromium analyses for the simulant exceeded the UTS; however, the granular product made using radioactive waste passed TCLP for all RCRA metals including chromium. The IOC, added to enhance denitration, could potentially be used as a co-reactant to sequester chromium as $FeCr_2O_4$ (SRNL-STI-2011-00387).

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – For 1 gallon of LAW feed: 1.0 gallon of primary waste form, 0.018 gallons of spent equipment, HEPA filters, spent carbon sorbent, etc., and no grouted solids (from ETF) (RPP-RPT-63580, *Calculating the Non-Monetary Impact of Operating a Fluidized Bed Steam Reforming Facility*, and SRNL-STI-2011-00387).

1.2. Long-term risks upon successful completion
Exogenous risks (earthquake, catastrophic flood, volcano, etc.) are assessed as indistinguishable across all technologies and disposal locations.
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics/destruction of organics – Presumably, all of the organics in the waste would be destroyed in the DMR or in the TO.

1.2.1.2. Nitrates/nitrites – High confidence that nitrate and nitrite will be nearly completely destroyed by the immobilization process. Testing done on varying conditions for over 20 years confirms thermodynamics of nitrated compounds – they thermally decompose at temperatures <400°C (i.e., well below 725-750°C in the DMR) and are destroyed to at or below detection limits in the mineralized product.

1.2.1.3. Ammonia/ammonium ion – None in primary waste form. No ammonia is added to the process. Ammonium compounds like ammonium nitrate and ammonium hydroxide are thermodynamically unstable or boil at temperatures above about 200°C, well below the 725-750°C temperature of the DMR. Ammonia and ammonium compounds are efficiently destroyed at temperatures typically between 850-950°C in the TO, which is designed to efficiently destroy thermally stable compounds such as hydrogen cyanide and benzene. But limited testing done on varying conditions and effectiveness of offgas system.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state. Expect essentially all mercury to sorb onto GAC based on pilot-scale testing but mercury retains its toxicity.

1.2.1.4.2. Chromium – High confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity in the Hanford environment.

1.2.2. Confidence in immobilization with regard to groundwater

1.2.2.1. Iodine – High-moderate confidence that partitioning of iodine through process will proceed as expected (i.e., iodine will primarily end up in the granular product). Single-pass capture is high and minimal amounts in secondary waste form (GAC).

Low leachability expected in waste form where leaching tests (e.g., PCT, SPFT) suggest normalized dissolution rates of the FBSR granular product are within the ranges of normalized dissolution rates for borosilicate glass with compositions within the processable compositions of Hanford's WTP (PNNL-14805; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063; PNNL-28838).[5] However, structural incorporation of iodine in the sodalite cage structure (as inferred from leaching results [SRNL-STI-2011-00387]) is uncertain – and thus is the long-term performance of the waste form for iodine during disposal – because no solid phase measurements (for iodine) have been performed to confirm the structural incorporation hypothesis. However, there is direct evidence of iodine incorporation into sodalite cages in studies focused on vapor-phase capture of iodine using sodalite materials (Maddrell et al., 2014; Sava et al., 2011), which suggests that iodine may also be structurally incorporated in the steam reforming granular product sodalite phase. Corrosion testing of FBSR granular products has also shown apparent congruent releases of iodine and technetium/rhenium, providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016) (see Section 1.1.2.1.1).

1.2.2.2. Technetium (including non-pertechnetates) – High confidence that nearly all technetium is captured in primary waste form; remainder (minimal) is captured in HEPA filters. Non-pertechnetate would be expected to decompose in DMR and behave similar to pertechnetate from waste. Low leachability in waste form. Structural incorporation of technetium in the sodalite cage structure (as inferred from leaching results [SRNL-STI-2011-00387]) is uncertain – and thus also is the long-term performance of the waste form for technetium – because no solid phase measurements (for technetium) have been performed. To date, only rhenium has been shown to exist in the sodalite cage resulting from steam reforming of Hanford LAW (Dickson et al., 2014; Mattigod et al., 2006; Dickson et al., 2015; Pierce et al., 2014). Rhenium can be a suitable surrogate for technetium, and it was inferred that technetium could also be incorporated into the sodalite cage of the FBSR product. Corrosion testing of FBSR granular products has shown apparent congruent releases of iodine and technetium/rhenium providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016). Furthermore, the fraction of technetium that would not be structurally incorporated in the sodalite cage would be insoluble in the oxide and/or sulfide form (SRNL-STI-2011-00387). Thus, the release of technetium not structurally incorporated in sodalite would be expected to be low as long as the waste form remains reduced (i.e., is not reoxidized) (see Section 1.1.2.1.2).

1.2.2.3. ^{79}Se – Medium confidence that selenium will behave similarly to sulfur and be incorporated into primary waste form with low leach rates. Spiked non-radioactive selenium found to pass RCRA limits by TCLP testing, indicating retention in the waste form (SRNL-STI-2011-00387). Chemistry is expected to mimic sulfur. High confidence in small inventory, 144 Ci total (per RPP-ENV-58562).

[5] Release rates are expected to be near or more likely well below the 2 g/m^2 target (ASTM C1285 [PCT]) for the FBSR granular product and monoliths (SRNL-STI-2011-00387) (see Section 1.1.2.1.1).

1.2.2.4. Nitrates/nitrites – High confidence that nitrate/nitrite will not impact groundwater due to destruction during process.

1.2.2.5. Ammonia/ammonium ion – Destroyed in TO. None in primary or secondary (GAC/HEPA filter) waste form.

1.2.2.6. RCRA metals – High confidence that most RCRA metals with sufficient inventory (except mercury) would be effectively immobilized in primary waste form with low TCLP leach rates. Mercury is partitioned entirely to secondary waste streams (GAC).

1.2.2.6.1. Mercury – Expect to be absorbed primarily in sulfur-impregnated carbon bed.

1.2.2.6.2. Chromium – Expect to be retained well in reduced granular primary waste form initially (that may also require additional IOC where this material is also used as a denitration aid in the FBSR process [SRNL-STI-2011-00387]), but no long-term testing on granular or monolith reoxidation has been performed.

1.2.2.6.3. Other RCRA metals – Other RCRA metals expected to be in granular primary waste form and not expected to be leachable via TCLP. TCLP leaching values for antimony and cadmium exceeded UTS limits; however, these values were shimmed in the feed (without regard for TCLP) to allow quantitative evaluation of mass balance/offgas results. High confidence in small inventory of cadmium (not recorded inventory in BBI because only small quantities of these chemicals are present in the waste and analytical data are limited [HNF-SD-WM-TI-740]). Only ^{125}Sb is recorded in the BBI because only small quantities of the other antimony isotopes are likely present in the waste. The total activity of ^{125}Sb (~615 Ci) as of 2018 translated to less than 0.5 gram in all Hanford tank wastes.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – High-moderate confidence in volume reduction of primary waste form. Moderate confidence in amount of secondary waste generated.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage (see tank leak discussion in Volume I, Section 1.3.3 for more detail).] High risk. Startup in ~15 years and 3-year ramp up to full processing rate, moderate flexibility in processing rate, undemonstrated throughput/TOE, complex and unique components, and potentially high maintenance needs contribute to high risk of delays and therefore increases risk of additional leaks.

Startup of this process in ~15 years has increased risk of additional tank leaks since retrievals would be delayed vs. the schedule to support HLW, increasing time available for corrosion-induced leaks due to ongoing tank degradation.

Continuity of operations after startup – Loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative consumes the entire initial benchmark supplemental LAW treatment budget, providing no opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is no potential for reducing risk of leaks.

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Multiple hazards. The thermal process produces a granular and potentially dusty waste form, which contains radionuclides, increasing the risk for worker exposure if exposed to product dust. The size and scope of the operations increase the potential for worker exposure during normal operations. The presence of product dust in the process also increases the potential for worker exposure during maintenance. Engineered and administrative controls would be required to prevent worker exposure. Construction would be near operating radioactive facilities and ground contamination. Low volatility of rads but potential for radioactive dust (e.g., maintenance activities on offgas equipment or containers of granular product).

2.2.1.2. Chemical exposure – Multiple hazards. Various chemicals and feed materials are used in the FBSR process. Besides the supplemental LAW feed itself, the process feed streams include liquid nitrogen and oxygen, clay powder, coal, fuel oil, activated carbon, sodium hydroxide, and sodium silicate solution. Alumina is a required startup bed material. The process also produces gases (e.g., CO, NO, and NO_2) that are irritants or toxic above certain concentrations. While these gases are efficiently destroyed in the process, they can exist in any gas leaks in worker spaces and would result in toxic, irritating, or O_2-deficient conditions. Dusts produced in the process can also include irritants or toxic chemicals. The size and scope of the operations increase the potential for worker exposure to gaseous or particulate chemical hazards during normal operation or maintenance. These hazards require mitigation through engineered and administrative controls.

2.2.1.3. Particulate exposure

Multiple hazards. Dry process feed streams (clay, coal, activated carbon), alumina in the startup bed, and the dry product waste form (prior to forming a monolith) contain dusts that require engineered and administrative controls to prevent exposure to workers during operations and maintenance. Product is granular with potential dust from the process gas filters (PGF). Radioactive dust is contained within process equipment.

2.2.1.4. Physical injury – The FBSR process includes various potential physical hazards, including mechanical, high temperature, cryogenic O_2 and N_2, dust, and low-O_2 hazards, all of which require mitigation during construction, operation and maintenance. 34 high hazards conditions were noted by WRPS for FBSR treatment of LAW (RPP-RPT-63580). Engineered controls mitigate hazards; construction/design will mitigate.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad.] [MOE: Few trip/shipments of rad/hazardous shipments to high number of rad/hazardous shipments.] – Moderate risk. The FBSR alternative that disposes primary waste form in IDF generates the mid-range waste volume and all waste is expected to be disposed of in the IDF leading to low transportation risk. Granular waste volume is ~1× the liquid waste volume (bounding value of 1.2× used for calculations).

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Low risk. Water is not incorporated in the primary waste form. Water is added during the treatment process for steam production and temperature quenching. This water is all evaporated and exits the stack; no liquid secondary wastes are produced. For the geopolymer monolith primary waste form option, water is added that becomes part of the solid monolith waste form. (Tritium is all released to the environment [stack] immediately.) Minimal liquid to ETF (no process liquids, only other types of liquid wastes such as potential decon solutions).

2.3.2. Atmospheric discharges

[MOE: Fraction of radionuclides and CoCs converted to vapor in offgas system.] – Atmospheric radionuclide and CoC discharges will be within regulatory limits and are not expected to be a discriminator. Oxidation of organic CoCs, mercury capture, $^{129}I/^{99}Tc/^{14}C$ capture, destruction of nitrates and NO_x, gas scrubbing, and filtration for both vitrification and FBSR are expected to achieve regulatorily compliant results for air emissions.

2.3.3. Transfer/process tank (on-site) spills

[Unplanned discharges MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Minimal risk of on-site spills (all transfer lines have secondary containment). No liquids are discharged from facility.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – No shipments of liquid and no off-site immobilized waste in the case of disposal at IDF. Off-site transportation risks include delivery of chemicals, including liquids such as sodium hydroxide, coal, clay, alumina, liquid oxygen, liquid nitrogen, and other industrial chemicals.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment); low quantity of secondary waste to highest quantity of liquids, solids, and equipment.] – No secondary liquid wastes are generated. Moderate amount of debris (spent GAC and HEPA filters comparable to vitrification).

2.3.6. Greenhouse gas emissions (see Section 2.3.2 above) – At a minimum, treatment of 1 Mgal of waste consumes 984 MT of coal (~3,200 MT CO_2), 200,000 gal fuel oil or natural gas (~2,100 MT CO_2), 19 GWh of electricity, and requires nearly 416 deliveries of clay, coal, and process chemicals (based on data from RPP-RPT-63580).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) – ~15 years.

2.4.2. Duration to full capacity (additional years) – The Integrated Waste Treatment Unit (IWTU) at Idaho National Laboratory (INL) has required about 9 years (up to now) to start radioactive feed after initial plant startup, which was mainly due to lack of technology maturation and several issues identified during IWTU plant startup that were neither identified nor resolved during preconstruction pilot/demonstration testing. With those IWTU lessons learned, time was included in the FBSR schedule estimate in the National Defense Authorization Act for Fiscal Year 2017 (NDAA17) study to provide for more extensive pilot/demonstration testing prior to supplemental LAW FBSR plant construction.

Considering IWTU plant startup experience, prior mineralizing FBSR demonstrations, and future pilot-scale FBSR demonstrations that would be performed as part of a project if selected for Hanford supplemental LAW treatment, time to full capacity for FBSR should be similar to vitrification, ~3 years.

2.4.3. Duration of operations (additional years) – The facility would operate until the end of the entire HLW campaign. HLW campaign will extend duration because the supplemental LAW processing starts later. Additional delay to supplemental LAW treatment startup extends the duration that existing equipment and WTP LAW melters must operate, exacerbating maintenance needs and requiring replacement of equipment and facilities that exceed their design life.

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues – High risk. Technology has not been demonstrated at scale with waste representing expected variability and uncertainty to produce a mineralized waste form in an integrated system. Feed system and offgas system are complex. Limited knowledge of waste form performance (i.e., lack of solid phase characterization to support structural incorporation inferences from leaching data, lack of thermodynamic and rate law data, and uncertainty quantification needed to predict long-term performance). (Delays due to technical uncertainties contribute to increased cost risk and therefore potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – High risk of delay. The FBSR is a complex system that includes many integrated subsystems that must all work together, or operations and maintenance costs may increase and exceed the annual budget.

3. Likelihood of successful mission

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk – Risks of things that would stop the project before completion (i.e., failure – which could be because the solution is cost/schedule prohibitive).

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste [i.e., failure mode likelihood and result] – this should be customized for each alternative with each unique failure mode and consequence)
[MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The FBSR alternative will use a similar feed flowsheet and approach as the existing WTP LAW Vitrification Facility, although the Hanford LAW FBSR uses a TO instead of a carbon reduction reformer (CRR), which was used at IWTU and found to be troublesome during startup. Portions of the steam reforming process have been extensively tested using pilot-scale systems, but for other applications (e.g., IWTU producing a carbonate waste form) and waste streams (e.g., sodium bearing waste at INL). Uncertainty remains in the partitioning of selected species (between product and offgas) and structural incorporation of ^{99}Tc and ^{129}I in sodalite (as inferred from leaching results and other circumstantial lines of evidence, as described in Section 1.1.2.1.1 and 1.1.2.1.2), but the baseline process is considered of moderate maturity to be able to put the waste sodium into a granular waste form. IWTU lessons will be incorporated, but with different flowsheet and waste form; consequence is that technology would be challenging. If a failure was imminent, it would likely be identified during pilot-scale testing.

3.1.1.1.1. Corrosion of offgas system causing frequent extensive repairs/ replacement – (Limited testing. Moderate temperatures. Halides are captured in DMR and do not vaporize appreciably.) – The commercial Erwin ResinSolutions Facility FBSR system (formerly Studsvik Processing Facility) in Erwin, Tennessee has operated since the 1990s, using similar mineralizing product chemistry (Mason et al., 1999). However, corrosion of the PGFs has been a cause of delay for the IWTU. This issue has been addressed with more pilot/demonstration testing and new filters (ceramic instead of Inconel, which corroded and caused plugging) have been installed in IWTU, and are now undergoing additional testing. Other potential corrosion issues include potential corrosion of offgas system piping, etc. during long-term operation, to be determined during IWTU operation. Corrosion is mitigated through process control and monitoring and avoided when operation is maintained within established operating limits. Consequence: Potential for frequent shutdown and component replacement, delaying the mission completion and high costs. Mitigated by operation of IWTU and pilot-scale testing that will help guide material of construction; moderately easy to shut down and restart).

3.1.1.1.2. Fire in offgas system – Low potential for fire in carbon bed or PGF. Potential for fire in the PGF is prevented by consumption of oxygen in the DMR, and subsequent minimal concentration of oxygen (close to 0 vol%) in the PGF. Supplemental LAW treatment is expected to contain organics and nitrates, which if not efficiently destroyed in the DMR and TO, could encourage oxidation of GAC particles and even fire in the carbon bed.

GAC is downstream of the oxidizer unit, which (together with the DMR) efficiently destroys organics. But some NO_x gas remains, along with about 3-5% O_2, in the oxidizer outlet gas. Potential for a fire in the carbon bed is mitigated through process control and monitoring of the gas composition and avoided when operation is maintained within established operating limits during normal FBSR operation. Consequence: CoC release to the environment, extended duration shutdown, system redesign/rebuild, delaying mission and additional costs.

3.1.1.1.3. Release of radioactive material (e.g., ^{129}I, ^{3}H) or other CoCs (e.g., mercury, NO_x) (above permit) to atmosphere (technetium/iodine radionuclides are not vaporized as much as with vitrification) – Risk is unexpected partitioning of species under DMR/PGF and offgas system processing due to operating conditions, or failure of offgas system components (TO, filters) to adequately destroy or capture CoCs. Consequence: Restore operating conditions back to within established operating limits (which are fast to accomplish) or, in the event of equipment failure, extended duration shut down, system redesign/rebuild, delaying mission and additional costs.

3.1.1.1.4. Ability to control offgas system as it ages (mitigate by replacing components on a schedule) – Low risk of unexpected partitioning of species under DMR/PGF and offgas system operating conditions. Consequence: Challenging operations, requiring periodic replacement of offgas system components (e.g., TO components, filters, or activated carbon) on planned or accelerated schedule without significant mission delay; or in the case of equipment failure, extended duration shut down, system redesign/rebuild.

3.1.1.1.5. Overall uncertainty of iodine partitioning – Low uncertainty. Liquid waste variability and rapid reactions could impact consistent partitioning (i.e., how much ends up in the offgas system) of the iodine. Consequence: Excess partitioning to offgas system requiring mitigation. Mitigated by adding/modifying components in the offgas system; determine need for required unit operations during pilot-scale testing.

3.1.1.1.6. Waste form leachability is higher than allowable – Radionuclide and hazardous metal retention based on the crystalline (sodalite/nosean) structure of the granular product and ability to consistently incorporate CoCs (especially iodine and technetium) in the sodalite cage structure and reducing chemistry in the granular product for technetium (SRNL-STI-2011-00387). Work has been done to demonstrate treatment effectiveness for selected Hanford LAW compositions (i.e., although not from designed studies) that do not adequately represent the variability and uncertainty in the Hanford LAW feeds that would likely need to be treated. This lack of representativeness translates to the consistency of the granular waste form produced from treating the high salt solution (with variabilities and uncertainties outside the tested ranges) in FBSR.

The hypothesis of structural incorporation of important radionuclides (^{129}I and ^{99}Tc) inferred from leaching results and supported by circumstantial lines of evidence (see Sections 1.1.2.1.1 and 1.1.2.1.2) and metal retention due to the reducing granular product require additional (designed) testing, but presumably these issues could be resolved prior to construction and startup. Consequence: High consequences that waste form leaches radionuclides or metals and cannot be disposed of without additional processing. (Mitigation method for off-specification material could include placing the product in a high integrity container (HIC), or off-site disposal in an acceptable commercial disposal site. Mitigation is assumed to not include sequestration by geopolymer.)

3.1.1.2. Process complexity [flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option]
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Very high complexity due to interconnectedness. FBSR of the supplemental LAW feed requires a large number of integrated unit operations and incorporation of variable streams. The thermal process generates an offgas that both requires extensive treatment prior to release and worker protections to prevent exposure. The process contains many items that require routine hands-on maintenance or replacement; however, the contact-handled nature of the proposed Hanford FBSR LAW would not require remote systems for repairing and replacing equipment in a heavily shielded environment, which has caused limitations for IWTU. The large and extensive treatment system represents an interdependent and complex system. The offgas system is similar to IWTU (without scrubber) and variations have been tested extensively in previous pilot-scale test rigs. The proposed FBSR for Hanford LAW is simpler in that a TO would be used instead of a CRR, which was troublesome during IWTU startup and had refractory issues (Farnsworth et al., 2019). A single unit operation failure in the system will slow or delay operations or even shut down the system. Consequence: Challenging to run system, delayed processing, additional costs, missed milestones.

3.1.1.2.1. Unit operations (21 systems listed below)[6]

- Feed preparation tasks
  - Clay feed system
  - Waste staging, mixing feed system (moderate complexity)
  - Additive feed system
  - Gas supply systems
- FBSR system
  - DMR (high complexity)
  - Spray nozzles (moderate complexity)
  - Process gas filter
  - Steam supply

[6] Very low or low complexity/consequences unless specified otherwise.

- Offgas system
  - Thermal oxidizer
  - Cooler
  - Carbon bed
  - Wet scrubber (if needed)
  - Reheater
  - Pre and HEPA filters
- Solids handling
  - Product handling system (moderate complexity)
  - Geopolymer additive system
  - Geopolymer mixer
  - Geopolymer product packaging
  - Geopolymer storing/curing
  - Container swabbing and decon station
  - Container load out station.

3.1.1.2.2. Accuracy of controls needed

- Sampling/measurements needed to control process – Very high complexity. Batch qualification is expected to give composition for clay/alumina amount where clay content and type are adjusted to account for alumina in the LAW (SRNL-STI-2011-00387). Process variability vs. clay/alumina composition and operating conditions has not been tested for a designated set of waste compositions to consistently achieve an acceptable crystalline structure (e.g., sodalite and nosean may form a solid solution; however, they are isostructural and contain a cage that could isolate CoCs). Consequence: Potential low throughput; poor product quality.

- Modeling needed to control process – Very high complexity. The FBSR process is driven by compositional requirements to produce a durable waste form (equivalent to the Na_2O-Al_2O_3-SiO_2 chemistry "shown to be acceptable" in 2001 with Tank AN-107 simulants) that is flowable, free of secondary phases, and of reliable durability. Reactions in the DMR gas phase occur within seconds, requiring a constantly vigilant process control system. Consequence: See items below. After solid phase measurements have confirmed inferences from leaching data of structural incorporation of ^{99}Tc and ^{129}I (with additional, supporting lines of evidence) and reoxidation of the granular waste form has been evaluated, a defensible product control system that accommodates variabilities and uncertainties in inputs (e.g., feed compositions), clay additives, etc. could be developed using the MINCALC™ system as a reasonable starting point.[7]
  Expect FBSR is moderately robust toward composition and operation with few parameters needed. Testing assumed during development would be used to develop/refine models/control process.
  - Failure modes for improper operation
    - Improper mineralized product production

[7] The evaluation of the long-term performance of the resulting steam reforming products (e.g., in a PA) would benefit greatly from additional information on the thermodynamic and rate model parameters needed to represent the dissolution of the steam reforming waste form in a PA to calculate a fractional release rate.

- Producing wrong mineral product or an amorphous product due to inability to control additives and process conditions would impact leachability and long-term performance of the radionuclides and metals from the waste form product.

– Off-normal waste feed composition
  - Variations in ratios of concentrations of elements captured in the primary waste form (e.g., sodium, chromium, halides, radionuclides) and their potential interactions can lead to variations in the primary waste form chemistry and mineralogy that may impact waste form performance.

– Improper coal/oxygen addition
  - Excess coal/insufficient oxygen addition causes higher levels of unreacted coal in the primary waste form and operating changes in the TO.
  - Insufficient coal/excess oxygen causes incomplete nitrate/NO_x destruction.

– Improper clay addition
  - Improper amount of clay results in inadequate mineral product formation, or higher volumes of primary waste form. Note that most of the pilot-scale studies were run using excess clay; however, subsequent BSR testing demonstrated that excess clay was not needed…[and helps] maximize Na_2O waste loadings (SRNL-STI-2011-00387 [p. 53]).

– Failure to control key temperatures in the DMR, PGF, TO, and offgas system
  - Temperatures too low could cause off-specification mineralized product, incomplete nitrate/NO_x destruction, incomplete organics/H_2 destruction, particulate filtration failure, or creation of aqueous secondary condensate.
  - Temperatures too high could cause filter failure, refractory failure, higher NO_x emissions, DMR slagging or fouling/scaling.

3.1.1.2.3. Commercially available/similar (of a type) to available/bespoke systems – High number of custom components. The supplemental LAW FBSR facility would be first-of-a-kind, but some components are used in related or other systems in use (e.g., product handling and packaging system, PGFs, GAC bed, and process blowers at IWTU). Thus, many of the IWTU lessons learned would be applicable, including ceramic PGFs and nozzle design. Entirely or relatively new for this application: DMR producing durable mineralized product; spray nozzles for an alkaline clay slurry; product handling system; configuration and integration of offgas system, geopolymer monolithing system; (and perhaps refractory lining of DMR). Consequence: Need to redesign/rebuild, causing mission delays.

3.1.1.2.4. Overall flowsheet integration complexity – Very high overall complexity. The flowsheet for an FBSR facility for supplemental LAW treatment is more complex than for a grouting facility and of similar complexity when compared to vitrification. The waste feed system includes batch analysis and metered addition of clay based on the feed analysis to produce the desired mineralized waste form with highest practical waste loading.

Multiple waste feed nozzles are used to feed the DMR, which has several other gaseous (steam, nitrogen, oxygen) and solid (coal) inputs; the feed rates of which must be controlled to maintain DMR operation within fluidized bed hydrodynamic and stoichiometric limits.

The mineralized product handling system includes equipment for collecting, pneumatic transferring, and cooling the mineralized product so that it can be formed, with geopolymer additives, into the geopolymer monolith product, in containers for storage, transport, and disposal.

The offgas system includes high and low-temperature (HEPA) filtration, thermal oxidation, GAC bed mercury absorption, wet scrubbing, and offgas cooling and reheating. The recycle of spent scrubber solution to the feed system can tolerate some additional variability to the waste feed composition that must be accounted for in the feed analyses and clay additive determinations.

Operating experience from WTP LAW Vitrification Facility will help with some design and operation that FBSR has in common with vitrification, including waste feed staging and mixing, the carbon bed, and HEPA filtration. IWTU operating experience will help with the DMR, PGF, product handling system, offgas cooler, carbon bed, and HEPA filtration. Industrial and commercial operating experience in other industries will help with design and operation of some FBSR unit operations, including liquid, solid, and gas transport (feed and product systems), product monolith (grouting) system, product storage and curing, and thermal oxidation. Consequence: Delayed processing, complex interrelated systems, DMR idling causing variability in waste form composition. Mitigated by experience at IWTU and years of testing assumed performed prior to construction.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed) – FBSR requires extensive utilities, including large demands for steam, cooling water, liquid oxygen, and liquid nitrogen, and process chemicals such as clay, coal, alumina, TO fuel (propane, natural gas, or fuel oil), sulfur-impregnated activated carbon, HEPA filters, and geopolymer additives (clay, sodium silicate, and NaOH).

Operating experience from IWTU, presuming it continues on its startup/operation path, would be applicable for all of this infrastructure except for the clay additive, TO fuel, and geopolymer additives. The infrastructure for the clay, TO fuel, and geopolymer additives is similar to relevant infrastructure in other industries. Cross-site supernatant liquid transfer line is needed to support this alternative.

Consequence: Delayed processing, complex interrelated systems, DMR idling causing variability in waste form composition due to addition of alumina (if the DMR is idled for 1-2 days based on IWTU experience but perhaps longer for the mineralized product) and continued addition of coal/oxygen/steam to maintain bed fluidizing; also causes attrition of particles in bed. If shutdown is required, can impact schedule and primary waste form properties. Further risk mitigation is provided in planned process demonstration at pilot- and demonstration-scale prior to full-scale supplemental LAW treatment system design.

3.1.1.4. Required demolition/removal/modification – It is expected that siting will not require demolition or removal of existing facilities. No consequences.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: Being completely ready to requiring development to make process work.] – Some aspects demonstrated. The FBSR alternative will use a new flowsheet and approach. Portions of the process have been tested using pilot- and full-scale systems. Uncertainty remains in the partitioning of selected species and in the long-term performance of essentially every FBSR unit operation which, while represented in other systems – including the WTP LAW melter systems and IWTU, Irwin, and pilot-scale simulant testing – will need to operate with the specific design and operation for supplemental LAW treatment. Consequence: Delayed processing and higher costs due to either process stoppage for redesign and process changes, or to more frequent or longer downtime for maintenance.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list) [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Low robustness. Recovery actions from things that go wrong include slowing or stopping the feed while performing corrective actions, process shutdown for redesign and process changes, or more frequent or longer downtime for maintenance. Based on prior FBSR experience at IWTU, unit operations most prone to failure or at least frequent maintenance include the feed systems, PGF, and product handling system. Consequence: Delayed processing and higher costs. Some mitigation by pilot-scale testing that would be performed prior to final design and operation.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques, place the waste form in HICs, or better isolate the waste form in IDF. Consequence: Retrieve the containerized material for alternate disposal or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions and flowrates
[High heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] Moderate adaptability. The ability to adjust waste loading and clay/alumina amounts (where clay content and type are adjusted to account for aluminum in the LAW feed) would allow an FBSR facility to handle a wide range of feeds. NRC (2011) concludes "…crystalline ceramic waste forms produced by FBSR have good radionuclide retention properties and waste loadings comparable to, or greater than, borosilicate glass."

However, the Hanford LAW compositions tested to date do not adequately represent those likely to be treated and more work (e.g., based on designed experiments) would help demonstrate process capability. Non-pertechnetate is not an issue for the FBSR process since any non-pertechnetate would likely react to form Tc(VII) in the DMR. Consequence: Delayed processing and higher costs. Mitigated by ability to analyze and blend waste feed in the feed system, use of two FBSR systems where one could be shut down for maintenance or during times of reduced demand.

3.1.4. Ability to incorporate future advances

[MOE: Easily incorporated to impossible.] – Moderate adaptability. The high capital cost and unique operations makes incorporation of future advances challenging. Consequence: High cost of changes.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.] – FBSR uses commonly available feed and start-up bed materials – water, steam, clay, coal, alumina, TO fuel (propane, natural gas, or fuel oil), sulfur-impregnated activated carbon, HEPA filters, and geopolymer additives (clay, sodium silicate, and NaOH). These are all common commercial and industrial materials. The likelihood of failure to resource constraints is low. The consequence of failure due to a constraint on any one of more of these materials is also low. For example, if one coal or clay becomes unavailable, then another of many other coal and clay options that have already been studied could be used. If one fuel for the TO becomes unavailable, other fuel options, some already studied, could be used.

3.2.1. Annual average spending

[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – The funding needs for a supplemental LAW FBSR facility will likely exceed the annual benchmark funding for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW only) against benchmark annual supplemental LAW treatment budget] – The peak funding needs for a supplemental LAW FBSR facility will likely greatly exceed the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – FBSR facilities can operate at perhaps ~10–20% of the design feed rate, but have limited ability to operate at lower rates. Idling the DMR at temperature with no waste feed is practicable for up to ~1–3 weeks but would require adding fluidized bed media to account for attrition and would cause contamination of the treated product with non-rad added bed media. The steam reforming equipment can be powered down almost instantaneously. The cold shutdown time for the Hanford LAW FBSR would be controlled by the cool down rate for the DMR because a TO would be used. Based on IWTU experience, it would likely take 2-3 days to go from operation for cold shutdown for the proposed Hanford LAW FBSR facility. Startup taking ~1-2 weeks would be a reasonable estimate for the proposed Hanford LAW FBSR facility. Using two FBSR facilities provides more flexibility than one because one or both can be operated at higher or lower feed rates, on idle (for up to about 1-3 weeks, or shut down, to match changes in feed supply.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – High potential failure is assumed to be caused by a lack of funding, and the failure point would occur during construction at peak spending. Consequence: Delayed mission due to lack of funding, delayed start of supplemental LAW treatment processing. Moderate amount of funding spent and time consumed prior to funding failure.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility starts and stops prior to startup. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to FBSR option, construct, and then funding is not allocated for startup. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – The supplier used for the FBSR is a single U.S. vendor that could go out of business. Consequence is DOE would assume the technology ownership and continue operations, potentially causing additional cost and delays. Calcined coal is typically added directly to the DMR bed as a fuel source and a reductant (SRNL-STI-2011-00387); however, the calcined coal used in IWTU has a single source in China. This supply chain should be evaluated if FBSR is selected for Hanford supplemental LAW treatment.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $5,527 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$3,375 M (includes commissioning costs)

4.2. Operations costs

$2,152 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.3 Selection Criteria Assessment for Alternative FBSR 1B

Alternative FBSR 1B: Fluidized Bed Steam Reforming – Off-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites – Low residual toxicity. Nitrate/nitrite are destroyed by FBSR and in the offgas system, are essentially nondetectable in the primary waste form, but the offgas still contains some NO_x gas species. Nitrates were destroyed to detection limit levels (0.002 wt%) in the mineralized product, and overall offgas NO_x destruction was measured at between 91-94%, exceeding the goal for the Hanford LAW and WTP secondary waste simulants tests. (RT-21-002, *Report for Treating Hanford LAW and WTP SW Simulants: Pilot Plant Mineralizing Flowsheet*). Trace amounts of nitrate in the primary waste form would be insignificant in the disposal environment.

1.1.1.2. RCRA metals – High residual toxicity. RCRA metals are contained in the primary waste form except for mercury. All mercury is presumed to evolve to the offgas. All primary offgas components will have mercury contamination and secondary offgas components will have mercury contamination up to the GAC. mercury captured on the sulfur-impregnated GAC would be micro-encapsulated in grout. No destruction.

1.1.1.3. LDR organics – Low residual toxicity. Most organics are destroyed by the FBSR and secondary offgas process. Some organics may be generated by incomplete combustion of coal but would be destroyed in the TO. Organics in waste largely destroyed to non-detectable levels in the primary waste form, remaining organics destroyed in offgas system to within regulatory limits. Leftover coal in primary waste form, but not believed to be an issue.

1.1.1.4. Ammonia – Very Low residual toxicity. The FBSR process should destroy whatever ammonia is in the LAW and process does not introduce ammonia into the system. Ammonia and related compounds are likely produced in the DMR but expect complete destruction in TO. Regardless, no ammonia for long term impact.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides
[MOE: Estimated peak groundwater concentration at compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection).]. There is no known pathway to potable water for off-site disposal and Hanford Site groundwater would be unaffected; therefore, only TCLP leaching results (see below) are relevant.

1.1.2.1.1. Iodine – Iodine is expected to partition predominately to the granular product. No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements. Some iodine may be sorbed onto the GAC, quantity is uncertain. Release rates from GAC for iodine are untested.

1.1.2.1.2. Technetium (Non-pertechnetate was evaluated in Section 1.2.2.2) – Most (~99%) ^{99}Tc will be retained in the primary granular waste form that has no impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site. A small fraction will be captured on the HEPA filters, which are crushed and macroencapsulated in grout. Leach rates from the spent HEPA filters are evaluated in the current PA, but the inventory to be disposed of is TBD. Expect about same amount on HEPA filters as in vitrification. Better single-pass retention of technetium in primary waste form vs. vitrification, leading to less technetium in offgas/HEPA filters.

1.1.2.1.3. Selenium-79 (^{79}Se) – Assumed to partition like sulfur, with most ending up in the primary waste form with no impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site. Like ^{99}Tc, a small portion could be captured on the spent HEPA filters that are macroencapsulated and disposed of in IDF. Expect about same amount on HEPA filters as in vitrification. Minimal impact due to low inventory (114 Ci; see Volume I, Section E.3.1.3).

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE: Estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection).] – N/A – destroyed in DMR.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives.] – Ammonia in tank waste is destroyed in the FBSR process. DMR may produce ammonia but will be destroyed in the TO and not present in solid waste form.

1.1.2.4. RCRA metals – [MOE is leachate TCLP compliance.] – Leach rates of RCRA metals from the granular waste are expected to be very low either from the nature of the granular product or low inventory in the LAW feed (SRNL-STI-2011-00387, *Fluidized Bed Steam Reformed Mineral Waste Form Performance Testing to Support Hanford Supplemental Low Activity Waste Immobilization Technology Selection*).[1] Only exceedances of TCLP UTS limits to date were for elements intentionally spiked above realistic limits.

1.1.2.4.1. Mercury – [MOE is retention of mercury in primary vs. secondary waste form.] – Mercury will not be retained in granular product and will end up in the activated carbon waste form, which is assumed to be encapsulated in grout. Expect granular waste form and encapsulated GAC grout to pass TCLP.

1.1.2.4.2. Chromium – [MOE is retention of Cr in waste form.] – Cr will be captured in the primary waste form with very low TCLP leach rates, although additional IOC may be required where this material is also used as a denitration aid in the FBSR process (SRNL-STI-2011-00387). Like technetium, a small fraction could be partitioned to the spent HEPA filters that are macroencapsulated in grout and disposed of in IDF. Expect granular waste form to pass TCLP. No long-term oxidation testing.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals is not known is but expected to pass TCLP. TCLP leaching values for antimony and cadmium exceeded UTS limits; however, these values were shimmed in the feed (without regard for TCLP) to allow quantitative evaluation of mass balance/offgas results. High confidence in small inventory of cadmium (where inventory not recorded in BBI [2018]) because only small quantities of these chemicals are present in the waste and analytical data are limited (HNF-SD-WM-TI-740, *Standard Inventories of Chemicals and Radionuclides in Hanford Site Tank Wastes*). Only ^{125}Sb is recorded in the BBI (2018) because only small quantities of the other antimony isotopes are likely present in the waste. The total activity of ^{125}Sb (~615 Ci) as of 2018 translated to less than 0.5 gram in all Hanford tank wastes.

[1] TCLP analyses for most of the RCRA metals were well below corresponding UTS (40 CFR 268.48, "Universal Treatment Standards," Non-wastewater) (SRNL-STI-2011-00387). However, some TCLP analyses for antimony, cadmium, and chromium exceeded UTS limits depending on the laboratory performing the analyses. After additional evaluation (including inventory considerations for cadmium and antimony), only the chromium analyses for the simulant exceeded the UTS; however, the granular product made using radioactive waste passed TCLP for all RCRA metals including chromium. The IOC, added to enhance denitration, could potentially be used as a co-reactant to sequester chromium as $FeCr_2O_4$ (SRNL-STI-2011-00387).

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – For 1 gallon of LAW feed: 1.0 gallon of primary waste form, 0.018 gallons of spent equipment, and no grouted solids (from ETF totals) (RPP-RPT-63580, *Calculating the Non-Monetary Impact of Operating a Fluidized Bed Steam Reforming Facility*, and SRNL-STI-2011-00387).

1.2. Long-term risks upon successful completion
Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics/destruction of organics – Presumably, all of the organics in the waste would be destroyed in the DMR or in the TO.

1.2.1.2. Nitrates/nitrites – High confidence that nitrate and nitrite will be nearly completely destroyed by the immobilization process. Testing done on varying conditions for over 20 years confirms thermodynamics of nitrated compounds – they thermally decompose at temperatures <400°C (i.e., well below 725-750°C in the DMR) and are destroyed to at or below detection limits in the mineralized product.

1.2.1.3. Ammonia/ammonium ion – None in primary waste form. Ammonium compounds like ammonium nitrate and ammonium hydroxide are thermodynamically unstable or boil at temperatures above about 200°C, well below the 725-750°C temperature of the DMR. Ammonia and ammonium compounds are efficiently destroyed at temperatures typically between 850-950°C in the TO, which is designed to efficiency destroy thermally stable compounds such as hydrogen cyanide and benzene. But limited testing done on varying conditions and effectiveness of offgas system.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state. Expect essentially all mercury to sorb onto GAC based on pilot-scale testing but mercury retains its toxicity.

1.2.1.4.2. Chromium – High confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with regard to groundwater

1.2.2.1. Iodine – High-moderate confidence that partitioning of iodine through process will proceed as expected. No impact to Hanford groundwater if all partitions to primary waste form. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements. Single-pass capture is high and minimal amounts in secondary waste form (GAC). Low leachability in waste form.

1.2.2.2. Technetium (including non-pertechnetates) – High confidence that nearly all technetium is captured in primary waste form; remainder (minimal) is captured in HEPA filters. Non-pertechnetate would be expected to decompose in DMR and behave similar to pertechnetate from waste. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.3. ^{79}Se – Medium confidence that selenium will behave similarly to sulfur and be incorporated into primary waste form. Chemistry is expected to mimic sulfur, but ^{79}Se is untested for FBSR. Spiked nonradioactive selenium in waste form found to pass TCLP testing, RCRA compliant (SRNL-STI-2011-00387). Small inventory, 144 Ci total (per RPP-ENV-58562). No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.4. Nitrates/nitrites – High confidence that nitrate/nitrite will not impact groundwater due to destruction during process.

1.2.2.5. Ammonia/ammonium ion – Destroyed in TO. None in primary or secondary (GAC/HEPA filter) waste form.

1.2.2.6. RCRA metals - High confidence that most RCRA metals with sufficient inventory (except mercury) would be effectively immobilized in primary waste form with low leach TCLP rates. No impact to Hanford groundwater (other than mercury). Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements. Mercury is partitioned entirely to secondary waste streams (GAC).

1.2.2.6.1. Mercury – Expect to be absorbed primarily in sulfur-impregnated carbon bed.

1.2.2.6.2. Chromium – Expect to be retained well in reduced granular primary waste form initially (that may also require additional IOC where this material is also used as a denitration aid in the FBSR process [SRNL-STI-2011-00387]). No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will likely comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.6.3. Other RCRA Metals – Other RCRA metals expected to be in granular primary waste form. TCLP leaching values for antimony and cadmium exceeded UTS limits; however, these values were shimmed in the feed (without regard for TCLP) to allow quantitative evaluation of mass balance/offgas results. High confidence in small inventory of cadmium (not recorded inventory in BBI) because only small quantities of these chemicals are present in the waste and analytical data are limited (HNF-SD-WM-TI-740). Only ^{125}Sb is recorded in the BBI because only small quantities of the other antimony isotopes are likely present in the waste.

The total activity of ^{125}Sb (~615 Ci) as of 2018 translated to less than 0.5 gram in all Hanford tank wastes and exhibits low leach rates. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.3. Confidence in total volume of primary and secondary waste forms produced - High-moderate confidence in volume reduction of primary waste form. Moderate confidence in amount of secondary waste generated.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk.

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage (see tank leak discussion in Volume I, Section 1.3.3 for more detail).] – High risk. Startup in ~15 years and 3-year ramp up to full processing rate, moderate flexibility in processing rate, undemonstrated throughput/TOE, complex and unique components, and high maintenance needs contribute to high risk of delays and therefore increases risk of additional leaks.

Startup of this process in ~15 years has increased risk of additional tank leaks since retrievals would be delayed vs. the schedule to support HLW, increasing time available for corrosion-induced leaks due to ongoing tank degradation.

Continuity of operations after startup – Loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative consumes the entire initial benchmark LAW supplemental treatment budget, providing no opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is no potential for reducing risk of leaks.

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Multiple hazards. The thermal process produces a granular and potentially dusty waste form, radionuclides, increasing the risk for worker exposure if exposed to product dust. The size and scope of the operations increase the potential for worker exposure during normal operations. The presence of product dust in the process also increases the potential for worker exposure during maintenance. Engineered and administrative controls would be required to prevent worker exposure. Construction would be near operating radioactive facilities and ground contamination. Low volatility of rads but potential for radioactive dust (e.g., maintenance activities on offgas equipment or containers of granular product).

2.2.1.2. Chemical exposure – Multiple hazards. Various chemicals and feed materials are used in the FBSR process. Besides the supplemental LAW feed itself, the process feed streams include liquid nitrogen and oxygen, clay powder, coal, fuel oil, activated carbon, sodium hydroxide, and sodium silicate solution.
Alumina is a required startup bed material. The process also produces gases (e.g., CO, NO, and NO_2) that are irritants or toxic above certain concentrations. While these gases are efficiently destroyed in the process, they can exist in any gas leaks in worker spaces, and would result in toxic, irritating, or O_2-deficient conditions. Dusts produced in the process can also include irritants or toxic chemicals. The size and scope of the operations increase the potential for worker exposure to gaseous or particulate chemical hazards during normal operation or maintenance. These hazards require mitigation through engineered and administrative controls.

2.2.1.3. Particulate exposure – Multiple hazards. Dry process feed streams (clay, coal, activated carbon), alumina in the startup bed, and the dry product waste form (prior to forming a monolith) contain dusts that require engineered and administrative controls to prevent exposure to workers during operations and maintenance. Product is granular with potential dust from PGF. Radioactive dust is contained within process equipment.

2.2.1.4. Physical injury – The FBSR process includes various potential physical hazards, including mechanical, high temperature, cryogenic O_2 and N_2, dust, and low-O_2 hazards, all of which require mitigation during construction, operation and maintenance. 34 high hazards conditions were noted by WRPS for FBSR treatment of LAW (RPP-RPT-63580). Engineered controls mitigate hazards; construction/design will mitigate.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad.] [MOE: Few trip/shipments of rad/hazardous shipments to high number of rad/hazardous shipments.] – Moderate risk. The FBSR alternative that disposes primary waste form off-site generates the mid-range waste volume and all waste is expected to be disposed of offsite leading to moderate transportation risk. Many off-site transports of solid radioactive waste form packages to distant location(s). Practical impact will be negligible since transport of low dose radioactive materials is well known. Granular waste volume is ~1× the liquid waste volume (bounding value of 1.2× used for calculations).

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Low risk. Water is not incorporated in the primary waste form. Water is added during the treatment process for steam production and temperature quenching. This water is all evaporated and exits the stack; no liquid secondary wastes are produced. (Tritium is all released to the environment [stack] immediately). Minimal liquid to ETF (e.g., decon solutions).

2.3.2. Atmospheric discharges
[MOE: Fraction of radionuclides and CoCs converted to vapor in offgas system.] – Atmospheric radionuclide and CoC discharges will be within regulatory limits and not expected to be discriminator. Oxidation of organic CoCs, mercury capture, $^{129}I/^{99}Tc/^{14}C$ capture, destruction of nitrates and NO_x, gas scrubbing, and filtration for both vitrification and FBSR are expected to achieve regulatorily compliant results for air emissions.

2.3.3. Transfer/process tank (on-site) spills
[Unplanned discharges MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Minimal risk of on-site spills (all transfer lines have secondary containment). No liquids are discharged from facility.

2.3.4. Off-site transportation spills
[MOE: No risk of off-site spills to high risk for off-site spills] – No shipments of liquid and no off-site immobilized waste in the case of disposal at IDF. Off-site transportation risks include delivery of chemicals, including liquids such as sodium hydroxide, coal, clay, alumina, liquid oxygen, liquid nitrogen, and other industrial chemicals. Possible transport incidents of granular waste form, but negligible release of radionuclides expected.

2.3.5. Secondary waste streams generated
[MOE: Volume of waste (liquid and solids and equipment); low quantity of secondary waste to highest quantity of liquids, solids, and equipment.] – No secondary liquid wastes are generated. Moderate amount of debris (spent GAC and HEPA filters comparable to vitrification).

2.3.6. Greenhouse gas emissions (see Section 2.3.2 above) – At a minimum, treatment of 1 Mgal of waste consumes 984 MT of coal (~3,200 MT CO_2), 200,000 gal fuel oil or natural gas (~2,100 MT CO_2), 19 GWh of electricity, and requires nearly 416 deliveries of clay, coal, and process chemicals (based on data from RPP-RPT-63580).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) – ~15 years

2.4.2. Duration to full capacity (additional years) – While the IWTU at INL has required 9 years (up to now) to start radioactive feed after initial plant startup, that was mainly due to lack of technology maturation and several issues identified during IWTU plant startup that were neither identified nor resolved during preconstruction pilot/demonstration testing. With those IWTU lessons learned, time was included in the FBSR schedule estimate in the NDAA17 study to provide for more extensive pilot/demonstration testing prior to FBSR LAW supplement treatment plant construction. Considering IWTU plant startup experience, prior mineralizing FBSR demonstrations, and future pilot-scale FBSR demonstrations that would be performed as part of a project if selected for Hanford LAW supplemental treatment, time to full capacity for FBSR should be similar to vitrification, ~3 years.

2.4.3. Duration of operations (additional years) – The facility would operate until the end of the entire HLW campaign. HLW campaign will extend duration because the LAW supplemental treatment processing starts later. Additional delay to LAW supplemental treatment startup extends the duration that existing equipment and first LAW melters must operate, exacerbating maintenance needs and requiring replacement of equipment and facilities that exceed their design life.

2.4.4. Risk of additional delay

2.4.4.1. Delay due to technical issues – (High risk) Technology has not been demonstrated at scale with waste representing expected variability and uncertainty to produce waste form in an integrated system. Feed system and offgas system are complex. (Delays due to technical uncertainties contribute to increased cost risk and therefore potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – High risk of delay. The FBSR is a complex system that includes many integrated subsystems that must all work together, or operations and maintenance costs may increase and exceed the annual budget.

3. Likelihood of successful mission

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk – Risks of things that would stop the project before completion (i.e., failure – which could be because the solution is cost/schedule prohibitive).

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste [i.e., failure mode likelihood and result] – this should be customized for each alternative with each unique failure mode and consequence)
[MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The FBSR alternative will use a similar feed flowsheet and approach as the existing WTP-LAW Vitrification Facility, although the Hanford LAW FBSR uses a TO instead of a CRR, which was used at IWTU and found to be troublesome during startup. Portions of the steam reforming process have been extensively tested using pilot-scale systems, but for other applications (e.g., IWTU producing a carbonate waste form) and waste streams (e.g., sodium bearing waste at INL). The baseline process is considered moderate maturity to be able to put the waste sodium into a granular waste form. IWTU lessons will be incorporated, but with different flowsheet and waste form; consequence is that technology would be challenging. If a failure was imminent, it would likely be identified during pilot-scale testing.

3.1.1.1.1. Corrosion of offgas system causing frequent extensive repairs/replacement – (Limited testing. Moderate temperatures. Halides are captured in DMR and do not vaporize appreciably.) The commercial Erwin ResinSolutions Facility FBSR system (formerly Studsvik Processing Facility) in Erwin, Tennessee has operated since the 1990s, using similar mineralizing product chemistry (Mason et al., 1999). However, corrosion of the PGFs has been a cause of delay for the IWTU. This issue has been addressed with more pilot/demonstration testing and new filters (ceramic instead of Inconel, which corroded and caused plugging) have been installed in IWTU and are now undergoing additional testing.

Other potential corrosion issues include potential corrosion of offgas piping, etc. during long-term operation, to be determined during IWTU operation. Corrosion is mitigated through process control and monitoring and avoided when operation is maintained within established operating limits. Consequence: Potential for frequent shutdown and component replacement, delaying the mission completion and high costs. Mitigated by operation of IWTU and pilot testing that will help guide material of construction; moderately easy to shut down and restart. (Note: idling is not practical

3.1.1.1.2. Fire in offgas system – Low potential for fire in carbon bed or PGF. Potential for fire in the PGF is prevented by consumption of oxygen in the DMR, and subsequent minimal concentration of oxygen (close to 0 vol%) in the PGF. LAW supplemental treatment is expected to contain organics and nitrates, which if not efficiently destroyed in the DMR and TO, could encourage oxidation of GAC particles and even fire in the carbon bed. GAC is downstream of the oxidizer unit, which (together with the DMR) efficiently destroys organics. But some NO_x gas remains, along with about 3-5% O_2, in the oxidizer outlet gas. Potential for a fire is mitigated through process control and monitoring of the gas composition and avoided when operation is maintained within established operating limits. Consequence: CoC release to the environment, extended duration shutdown, system redesign/rebuild, delaying mission and additional costs.

3.1.1.1.3. Release of radioactive material (e.g., ^{129}I, ^{3}H) or other CoCs (e.g., mercury, NH_3) (above permit) to atmosphere. (Technetium/iodine radionuclides are not vaporized as much as with vitrification) – Risk is unexpected partitioning of species under DMR/PGF and offgas system processing due to operating conditions, or failure of offgas system components (TO, filters) to adequately destroy or capture CoCs. Consequence: Restore operating conditions back to within established operating limits (which are fast to accomplish) or, in the event of equipment failure, extended duration shut down, system redesign/rebuild, delaying mission and additional costs.

3.1.1.1.4. Ability to control offgas system as it ages – Low risk of unexpected partitioning of species under DMR/PGF and offgas system operating conditions. (Mitigate by replacing components on a schedule). Consequence: Challenging operations, requiring periodic replacement of offgas system components (e.g., TO components, filters, or activated carbon) on planned or accelerated schedule without significant mission delay; or in the case of equipment failure, extended duration shut down, system redesign/rebuild.

3.1.1.1.5. Overall uncertainty of iodine partitioning. Low uncertainty. Liquid waste variability and rapid reactions could impact consistent partitioning (i.e., how much ends up in the offgas system) of the iodine. Consequence: Excess partitioning to offgas system requiring mitigation.

Mitigated by adding/modifying components to the offgas system; determine required unit operations during pilot-scale testing.

3.1.1.1.6. Waste form leachability is higher than allowable – Radionuclide leaching is not a criterion for off-site disposal, but waste form must be RCRA-compliant for hazardous metals. Consequence: Waste form leaches metals that exceed UTS limits and cannot be disposed of without additional processing. Mitigation methods for off-specification material have not been investigated.

3.1.1.2. Process complexity [flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option]
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Very high complexity due to interconnectedness. FBSR of the supplemental LAW feed requires a large number of integrated unit operations and incorporation of variable streams into the feed process. The thermal process generates an off gas that both requires extensive treatment prior to release as well as worker protections to prevent exposure. The process contains many items that require routine hands-on maintenance or replacement; however, the contact-handled nature of the proposed Hanford FBSR LAW would not require remote systems for repairing and replacing equipment in a heavily shielded environment, which has caused limitations for IWTU. The large and extensive treatment system represents an interdependent and complex system where not all interactions are well understood. Offgas system is similar to IWTU (without scrubber) and variations have been tested extensively in previous pilot-scale test rigs. The proposed FBSR for Hanford LAW is simpler in that a TO would be used instead of a CRR, which was troublesome during IWTU startup and had refractory issues (Farnsworth et al., 2019). A single unit operation failure in the system will slow operations or even shut down the system (high interconnectedness). Consequence: Challenging to run system, delayed processing, additional costs, missed milestones.

3.1.1.2.1. Unit operations (17 systems listed below)[2]

- Feed preparation tasks
  - Clay feed system
  - Waste staging, mixing feed system (moderate complexity)
  - Additive feed system
  - Gas supply systems
- FBSR system
  - DMR (high complexity)
  - Spray nozzles (moderate complexity)
  - Process gas filter (moderate complexity)
  - Steam supply
- Offgas system
  - Thermal oxidizer

[2] Very low or low complexity/consequences unless specified otherwise.

  - Cooler
  - Carbon bed
  - Wet scrubber
  - Reheater
  - Pre and HEPA filters
- Solids handling
  - Product handling system (moderate complexity)
  - Container swabbing and decon station (moderate complexity)
  - Container load out station

3.1.1.2.2. Accuracy of controls needed.

- Sampling/measurements needed to control process – Very high complexity. Batch qualification is expected to give composition for clay/alumina amount where clay content and type is adjusted to account for aluminum in the LAW waste (SRNL-STI-2011-00387). Process variability vs. clay/alumina composition and operating conditions is not tested for all waste compositions to consistently achieve acceptable partitioning. Consequence: Potential low throughput; poor product quality.
- Modeling needed to control process – Very high complexity. The FBSR process is driven by compositional requirements to produce a waste form that is flowable, free of secondary phases, and satisfies waste acceptance criteria (including TCLP for RCRA metals). Reactions in the DMR gas phase occur within seconds, requiring a constantly vigilant control system. Consequence: See items below. A defensible product control system that accommodates variabilities and uncertainties in inputs (e.g., feed compositions), clay additives, etc. could be developed using the MINCALC™ system as a reasonable starting point. Expect FBSR is moderately robust toward composition and operation with few parameters needed. Testing assumed during development would be used to develop/refine models/control process.
  - Failure modes for improper operation
    - Improper mineralized product production
      - Producing wrong mineral product or an amorphous product due to inability to control additives and process conditions would impact leachability (TCLP) of metals from the waste form product.
    - Off-normal waste feed composition
      - Variations in ratios of concentrations of elements captured in the primary waste form (e.g., sodium, chromium, halides, radionuclides) and their potential interactions can lead to variations in the primary waste form chemistry and mineralogy that may impact waste form leaching for metals (TCLP).
    - Improper coal/oxygen addition
      - Excess coal/insufficient oxygen addition causes higher levels of unreacted coal in the primary waste form and operating changes in the TO.
      - Insufficient coal/excess oxygen causes incomplete nitrate/NO_x destruction.

- Improper clay addition
  - Improper amount of clay results in inadequate mineral product formation, higher volumes of primary waste form, or higher feed slurry viscosity issues that could affect waste feeding and atomizing the slurry in the DMR. Note that most of the pilot-scale studies were run using excess clay; however, subsequent BSR testing demonstrated that excess clay was not needed… [and helps] maximize Na_2O waste loadings (SRNL-STI-2011-00387 [p.53]).
- Failure to control key temperatures in the DMR, PGF, TO, and offgas system.
  - Temperatures too low could cause off-specification mineralized product, incomplete nitrate/NO_x destruction, incomplete organics/H_2 destruction, particulate filtration failure, or creation of aqueous secondary condensate.
  - Temperatures too high could cause filter failure, refractory failure, higher NO_x emissions, DMR slagging or fouling/scaling.

3.1.1.2.3. Commercially available/similar (of a type) to available/bespoke systems – High number of custom components. The FBSR LAW supplemental treatment facility would be first-of-a-kind, but some components have one to two related systems in use (e.g., product handling and packaging system, PGFs, GAC bed, and process blowers at IWTU). Thus, many of the lessons learned at IWTU would be applicable, including ceramic PGFs and nozzle design. Entirely new for this application: DMR producing durable mineralized product; spray nozzles for an alkaline clay slurry; product handling system; configuration and integration of offgas system (and perhaps refractory lining of DMR). Consequence: Need to redesign/rebuild, causing mission delays.

3.1.1.2.4. Overall flowsheet integration complexity – Very high overall complexity. The flowsheet for an FBSR facility for LAW supplemental treatment is more complex than for a grouting facility and of similar complexity when complex compared to vitrification. The waste feed system includes batch analysis and metered addition of clay needed based on the feed analysis to produce the desired mineralized waste form with highest practical waste loading. Multiple waste feed nozzles are used to feed the DMR, which has several other gaseous (steam, nitrogen, oxygen) and solid (coal) inputs, the feed rates of which must be controlled to maintain DMR operation within fluidized bed hydrodynamic and stoichiometric limits.

The mineralized product handling system includes equipment for collecting, pneumatic transferring, and cooling the mineralized product in containers for storage, transport, and disposal.

The offgas system includes high and low-temperature (HEPA) filtration, thermal oxidation, GAC bed mercury absorption, wet scrubbing, and offgas cooling and reheating. The recycle of spent scrubber solution to the feed system can tolerate some additional variability to the waste feed composition that must be accounted for in the feed analyses and clay additive determinations.

Operating experience from WTP LAW Vitrification Facility will help with some design and operation that FBSR has in common with vitrification, including waste feed staging and mixing, the carbon bed, and HEPA filtration. IWTU operating experience will help with the DMR, PGF, product handling system, offgas cooler, carbon bed, and HEPA filtration.

Industrial and commercial operating experience in other industries will help with design and operation of some FBSR unit operations, including liquid, solid, and gas transport (feed and product systems), product monolith (grouting) system, product storage and curing, and thermal oxidation. Consequence: Delayed processing, complex interrelated systems, DMR idling causing variability in waste form composition. Mitigated by experience at IWTU and years of testing assumed performed prior to construction.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed) – FBSR requires extensive utilities, including large demands for steam, cooling water, liquid oxygen, and liquid nitrogen and process chemicals such as clay, coal, alumina, TO fuel (propane, natural gas, or fuel oil), sulfur-impregnated activated carbon, HEPA filters, and geopolymer additives (clay, sodium silicate, and NaOH). Operating experience from IWTU, presuming it continues on its startup/operation path, would be applicable for all of this infrastructure except for the clay additive and TO fuel. The infrastructure for the clay and TO fuel is similar to relevant infrastructure in other industries. Cross-site supernatant liquid transfer line is needed to support this alternative. Consequence: Delayed processing, complex interrelated systems, DMR idling causing variability in waste form composition due to addition of alumina (if the DMR is idled for 1-2 days based on IWTU experience but perhaps longer for the mineralized product) and continued addition of coal/oxygen/steam to maintain bed fluidizing; also causes attrition of particles in bed. If shutdown is required, can impact schedule and primary waste form properties. Further risk mitigation is provided in planned process demonstration at pilot- and demonstration-scale prior to full-scale LAW supplemental treatment system design.

3.1.1.4. Required demolition/removal/modification – It is expected that siting will not require demolition or removal of existing facilities. No consequences.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work] – Some aspects demonstrated. The FBSR alternative will use a new flowsheet and approach. Portions of the process have been tested using pilot-scale systems.

Uncertainty remains in the partitioning of selected species and in the long-term performance of essentially every FBSR unit operation which, while represented in other systems including the WTP LAW melter systems and IWTU, Irwin, and pilot-scale simulant testing, will need to operate with the specific design and operation for LAW supplemental treatment. Consequence: Delayed processing and higher costs due to either process stoppage for re-design and process changes, or to more frequent or longer downtime for maintenance.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list) [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Low robustness. Recovery actions from things that go wrong include slowing or stopping process operations for redesign and process changes, or for more frequent or longer downtime for maintenance. Based on prior FBSR experience at IWTU, unit operations most prone to failure or at least frequent maintenance include the DMR feed nozzles, DMR coal feed system, PGF, and product handling system. Consequence: Delayed processing and higher costs. Some mitigation by pilot-scale testing that would be performed prior to final design and operation.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions and flowrates
[High heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – The ability to adjust waste loading and clay/alumina amounts (where clay content and type are adjusted to account for aluminum in the LAW feed) will allow a FBSR facility to handle a wide range of feeds. NRC (2011) concludes "…crystalline ceramic waste forms produced by FBSR have good radionuclide retention properties and waste loadings comparable to, or greater than, borosilicate glass." However, the Hanford LAW compositions tested to date do not adequately represent those likely to be treated and more work (e.g., based on designed experiments) would help demonstrate process capability. Non-pertechnetate is not an issue for the FBSR process since any non-pertechnetate would likely react to form Tc(VII) in the DMR. Consequence: Delayed processing and higher costs. Mitigated by ability to analyze and blend waste feed in the feed system, use of two FBSR systems where one could be shut down for maintenance or during times of reduced demand.

3.1.4. Ability to incorporate future advances
[MOE: Easily incorporated to impossible.] – Moderate adaptability. The high capital cost and unique operations makes incorporation of future advances challenging. Consequence: High cost of changes.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.] – FBSR uses commonly available feed and startup bed materials – water, steam, clay, coal, alumina, TO fuel (propane, natural gas, or fuel oil), sulfur-impregnated activated carbon, HEPA filters, and geopolymer additives (clay, sodium silicate, and NaOH).

These are all common commercial and industrial materials. The likelihood of failure due to resource constraints is low. The consequence of failure due to a constraint on any one of more of these materials is also low. For example, if one coal or clay becomes unavailable, then another of many other coal and clay options that have already been studied could be used. If one fuel for the TO becomes unavailable, other fuel options, some already studied, could be used.

3.2.1. Annual average spending

[MOE: Annual average spending requirements against benchmark annual LAW supplemental treatment budget.] – The funding needs for an FBSR LAW supplemental treatment facility will likely exceed the benchmark funding level for a LAW supplemental treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW only) against benchmark annual LAW supplemental treatment budget.] – The peak funding needs for an FBSR LAW supplemental treatment facility will likely greatly exceed the benchmark funding level for a LAW supplemental treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – FBSR facilities can operate at perhaps ~10–20% of the design feed rate but have limited ability to operate at lower rates. Idling the DMR at temperature with no waste feed is practicable for up to ~1–3 weeks but would require adding fluidized bed media to account for attrition and would cause contamination of the treated product with non-rad added bed media. The steam reforming equipment can be powered down almost instantaneously. The cold shutdown time for the Hanford LAW FBSR would be controlled by the cool down rate for the DMR because a TO would be used. Based on IWTU experience, it would likely take 2-3 days to go from operation for cold shutdown for the proposed Hanford LAW FBSR facility. Startup taking ~1-2 weeks would be a reasonable estimate for the proposed Hanford LAW FBSR facility. Using two FBSR facilities provides more flexibility than one because one or both can be operated at higher or lower feed rates, on idle (for up to about 1-3 weeks), or shut down, to match changes in feed supply.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Potential failure is assumed to be caused by a lack of funding and the failure point would occur during construction at peak spending. Consequence: Delayed mission due to lack of funding, delayed start of LAW supplemental treatment processing. Moderate amount of funding spent and time consumed prior to funding failure.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility starts and stops prior to startup. Start of LAW supplemental treatment mission is delayed. Worst case is to commit to FBSR option, construct, and then funding is not allocated for startup. Consequence: delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones.

3.3. Likelihood and consequences of failing to complete due to unavailability of key services and materials

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – The supplier used for the FBSR is a single U.S. vendor that could go out of business. Off-site disposal location could cease receipt of waste or permission to transport is revoked for unforeseen reasons. Consequence is DOE would assume the technology ownership and continue operations, potentially causing additional cost and delays. Suspension of shipping would result in a ~2.5-month working inventory of material would remain onsite or in-transit until the issue is resolved (maximum of 425 containers if disposed of in 8.4 m^3 bags).

Calcined coal is typically added directly to the DMR bed as a fuel source and a reductant (SRNL-STI-2011-00387); however, the calcined coal used in IWTU has a single source in China. This supply chain should be evaluated if FBSR is selected for Hanford LAW treatment.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $6,279 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$3,374 M (includes commissioning costs)

4.2. Operations costs

$2,905 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.4 Selection Criteria assessment for Alternative Grout 1A

Alternative Grout 1A: Single Supplemental Low-Activity Waste Grout Plant – On-Site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – Iodine mobility to ground water is limited during the first 1,000 year compliance period. Iodine sequestered by getter leads to enhanced retention in waste form; relative to non-getter waste form. Projected ~100× below DWS (maximum contaminant level) per NDAA17 report but uncertainty in long-term performance with only laboratory data to date. Iodine not bound to getter can exceed DWS.

To limit mobility beyond the period of compliance, iodine requires stability of getter phase to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout.

1.1.2.1.2. Technetium (non-pertechnetate is evaluated below in confidence) [MOE will be projected concentration in groundwater.] – Technetium mobility to groundwater is limited during the first 1,000 years compliance period due to facility performance. Blast-furnace slag (BFS) sequesters technetium providing high performance for technetium; ~10× below DWS per NDAA17 report; uncertainty in rate of reoxidation of grout in IDF; an oxidized grout can exceed DWS. To limit mobility beyond the period of compliance, technetium requires maintenance of reducing conditions for a portion of the waste form during disposal to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3.1.3). Assuming high mobility from waste form release to subsurface is many orders of magnitude below conservative DWS.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE: Estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Nitrate/nitrite mobility to groundwater is limited during the first 1,000 year compliance period. Retained only by diffusion barrier (physical entrapment). Recent diffusivity testing shows some formulations can retain nitrate/nitrate more effectively and estimate peak concentrations below the compliance standard. These tests were performed in a conservative, saturated environment, which would produce much greater release rates than actual unsaturated conditions in the IDF. Conservative assumptions regarding nitrate/nitrate subsurface behavior can result in exceedance of DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3).

1.1.2.3. Ammonia – No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; ammonia stripped during evaporation is immobilized at ETF.] Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Waste form has reduced toxicity. Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be compliant.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form (grout redox chemistry).] – Cr(VI) sequestered by redox reactions with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty exists in rate of reoxidation of grout in IDF and change in waste form pH; an oxidized, neutral grout can exceed DWS for chromium. To limit mobility beyond the period of compliance chromium requires maintenance of reducing conditions for a portion of the waste form and maintain alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond period of compliance.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium.

1.1.3. Total volume of primary and secondary waste forms – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include the evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS. [MOE is volume of primary and all secondary waste forms.]

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in Hanford environment. Oxidation state and speciation could change vs. current state.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity in Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity in Hanford environment.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and in the resulting waste form as iodide with a fraction of iodate. Moderate confidence in the immobilization of AgI from reaction with getter in the waste form, but any unreacted free iodide/iodate is mobile. Success of the silver precipitation approach has been shown at the laboratory-scale using getters but not demonstrated at large scale. The immobile fractions as AgI can destabilize with time due to chemical reduction of Ag^{+} to Ag^{0} and competition with other species (e.g., sulfide which can form Ag_2S), the rate of these destabilization processes in the disposed waste form is untested. Iodine is a key constituent of interest in the IDF PA. ^{129}I can define waste classification but concentrations in Hanford tanks likely far lower than Class A limit[2]. Once released by chemical reactions and leached into the subsurface there is limited to no natural attenuation of iodide, and as such the supplemental LAW iodine inventory could impact groundwater in the post-compliance period. However, a complete assessment of any iodine impact in the post-compliance period must be evaluated in a performance assessment considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste as pertechnetate with a fraction of non-pertechnetate. Within the waste form, there is high confidence in the conversion of pertechnetate to a reduced and insoluble technetium, but there is an unknown behavior of non-pertechnetate. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form can be destabilized with time due to oxidation, but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA. Technetium can define waste classification, and select tanks have technetium concentrations that approach the Class A limit[3]. However, a complete assessment of any technetium impact in the post-compliance period must be evaluated in a performance assessment considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.3. ^{79}Se – Limited to no data available on the speciation in the waste, in grout, or mobility within grout waste forms. Limited attenuation in the Hanford subsurface.

[2] ^{129}I is listed in Table 1 of 10 CFR 61.55, "Waste Classification," that is used to classify wastes for near-surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

[3] ^{99}Tc is listed in Table 1 of 10 CFR 61.55, which is used to classify wastes for near-surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

High confidence of minimal impact due to minimal inventory (144 Ci or ~2 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*).

1.2.2.4. Nitrates/nitrites – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are mobile in grout waste forms and will not be slowed without formulation modification. Nitrate and nitrite are a key constituent within the IDF but will not drive waste classification or waste acceptance criteria. There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford tanks, and a recent assessment projected concentrations slightly above groundwater limits in the post-compliance period using a projection of a non-optimized grout waste form disposed of in IDF. As such, there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a performance assessment considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal impact.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – Very high confidence in ability to pass TCLP. High confidence in ability to sequester due to mercury sulfide formation but low confidence in mercury speciation in tank waste. High confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface.

1.2.2.6.2. Chromium – Very high confidence in sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in re-oxidation/solubilization rate in Hanford disposal environment, high confidence in knowledge of subsurface mobility; there is limited attenuation in the IDF backfill and subsurface although some mineral interactions (iron, carbonate, barium) have been observed. Chromate is slow moving in subsurface and expected to be compliant with DWS.

1.2.2.6.3. Other RCRA metals – Depends on metal. Moderate confidence on speciation in Hanford waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP, however, if Ag is added as iodine getter, this adds uncertainty.

1.2.3. Confidence in total volume of primary and secondary waste forms produced
High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk
[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage.] (See tank leak discussion in Volume I, Section 1.3.3 for more detail.) – Startup in ~13 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~13 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is more impactful because of dependence on cross site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety
[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction is near an operating radioactive facility (LAW Vitrification Facility); this single plant construction would be shorter duration in comparison to other alternatives.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (High consequence hazard is not applicable to this alternative since there is no vault.) Over 20 years of operation of Saltstone facilities at

Savannah River Site (SRS) demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: few trip/shipments to high number of shipments)] – Low risk. Large number of transports of raw materials onto site and waste form boxes onsite; no hazardous liquids shipped onsite; no rad liquid transport; no off-site transport of radioactive materials.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; all LAW/flush water during grouting is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[4]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered process vessel ventilation (PVV). Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Minimal risk, few tanks and process unit operations. Only risk is transfers to evaporator and LERF/ETF.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – Negligible risk. Only possible is material transport truck/railcar accident of non-rad minimally hazardous dry solid ingredients.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment].] – Very low volume. Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions

[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426).

[4] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~13 years

2.4.2. Duration to full capacity (additional years) 1 year

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delay

2.4.4.1. Delays due to technical/engineering issues – Minimal risk to delay operations due to grout technology; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*). (Delays due to technical uncertainties contribute to increased cost risk and therefore potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste.) [MOE: Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences; first score is likelihood, second is consequences.] – Low risk of failure. The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, and getters will be included, but engineering uncertainties are minimal. Uncertainty remains in the utility of getters at scale and LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence of failure to identify a suitable iodine getter or remedy results in failure in ability to dispose of onsite in IDF. Very high consequences.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading. Low consequences.

3.1.1.1.2. Suitable getter (iodine and potentially technetium) not identified/long-term performance inadequate – Medium likelihood and high consequence. While suitable getters for technetium and iodine have been tested in laboratory testing, the application of these getters in a production process and in conjunction with each other has not been demonstrated.

Consequence of not identifying a suitable getter would be that on-site disposal of the grout is not permitted and other methods to sequester iodine are not identified. Very high consequences.

3.1.1.1.3. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping. Very low consequences.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility but impacts in process delays could occur. Low consequences.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species. Low consequences.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: very low. Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[5]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – Vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container box disassembly and emplacement at IDF – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modeling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition. Moderate consequences.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10-unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites.

[5] Very low or low complexity/consequences, unless specified otherwise.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on co-located processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line is needed to support this alternative.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier.

3.1.1.5. Technology Maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.]
Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990) INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Adding iodine getters has not been demonstrated at scale. Shipping of containerized grout has been done (Nevada National Security Site [NNSS]). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Consequence: Additional development time needed, delayed processing.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Highly robust. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions

[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)

[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending

[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for a supplemental LAW grout facility will likely be beneath the annual benchmark funding for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for a supplemental LAW grout facility will likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – Very low likelihood of failure. Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Scenario is that operations more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not start or stops until funding is available. Start of the supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to complete a grout facility by the project need date.

3.3. Likelihood and consequences of failing to complete due to unavailability of key services and materials

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been pre-selected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $2,730 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,108 M (includes $80M commissioning)

4.2. Operations costs

$1,622 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.5 Selection Criteria Assessment for Alternative Grout 1B

Alternative Grout 1B: Single Supplemental Low-Activity Waste Grout Plant – Off-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.1.2. Technetium (confidence in non-pertechnetate is evaluated below) [MOE will be projected concentration in groundwater.] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci total in tank farm per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*). No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE: Estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection.] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.3. Ammonia – No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; no differences between alternatives; ammonia stripped during evaporation immobilized at ETF.] – Minimal impact to Hanford groundwater due to grouted ETF solids. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements. Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Mobility judged against TCLP which reducing grout consistently passes. Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory. Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.2. Chromium [MOE is retention of Cr in waste form (grout redox chemistry).] – Cr(VI) sequestered by redox w reductants in BFS and precipitation as hydroxide with alkali. Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.3. Other [No MOE needed.] – Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed at SALDS.

1.2. Long-term risks upon successful completion
[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – High confidence in no impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology.
The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in no impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.3. ^{79}Se – High confidence in no impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.4. Nitrates/nitrites – High confidence in no impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – Very high confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.2. Chromium – Very high confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.3. Other RCRA metals – Very high confidence in ability to pass TCLP/waste acceptance criteria. Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – Very high confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage.] (See tank leak discussion in Volume I, Section 1.3.3 for more detail.) – Startup in ~13 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks.

Startup of this process in ~13 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is more impactful because of dependence on cross site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction is near an operating radioactive facility (LAW Vitrification Facility); this single plant construction would be shorter duration in comparison to other alternatives.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure technetium Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury technetium Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (High consequence hazard is not applicable to this alternative since there is no vault). Over 20 years of operation of Saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)] – Low risk. Large number of transports of raw materials onto site and waste form boxes onsite; no hazardous liquids shipped onsite; no rad liquid transport; many off-site transports of solid radioactive waste form packages to distant location(s). Practical impact will be negligible since transport of low dose radioactive materials is well known.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal risk; all LAW/flush water is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[2]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

[2] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.3.2. Atmospheric discharges
[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)
[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Minimal risk, few tanks and process unit operations. Only risk is transfers to evaporator and LERF/ETF.

2.3.4. Off-site transportation spills
[MOE: No risk of off-site spills; high risk for off-site spills.] – Minimal risk. Possible material transport truck/railcar accident of non-rad minimally hazardous dry solid ingredients to Hanford Site. Possible transport incidents of grouted waste form, but negligible release of radionuclides expected.

2.3.5. Secondary waste streams generated
[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment).] – Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions
[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426). Expect shipments of ~46,000 grouted waste form boxes to distant disposal location(s) (see Volume II, Section H.9 for more information).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~13 years

2.4.2. Duration to full capacity (additional years) 1 year

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues00391 Minimal risk to delay operations; technology is well understood and demonstrated successfully at full scale in DOE complex. LDR removal has had only limited testing, but mitigation is to send non-compatible wastes to the LAW melter. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*).

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste). [MOE: Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – Low likelihood of failure. The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, and getters will be included, but engineering uncertainties are minimal. Uncertainty remains in LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence is low; reduced waste loading or diverting more waste to LAW melters.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading.

3.1.1.1.2. Transport lines become blocked/congested or leak – Very low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping.

3.1.1.1.3. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed enough to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidization methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP-LAW Vitrification Facility but impacts in process delays could occur.

3.1.1.1.4. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[3]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – Continuous stirred tank reactor vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations; train.
- Container box disassembly and emplacement at -off-site location(s) – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.

[3] Very low or low complexity/consequences, unless specified otherwise.

- Modeling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition. Moderate consequences.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites.

3.1.1.3. Required facilities/infrastructure (moderate complexity) (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on co-located processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line is needed to support this alternative.
- Rail line spur.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier. Off-site disposal locations may need expansion.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Shipping grouted LAW offsite has been demonstrated as part of the Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990) INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Adding iodine getters has not been demonstrated at scale. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford tank waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Consequence: Additional development time needed, delayed processing.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Very robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Very high robustness. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative. Low consequences.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for a supplemental LAW grout facility will likely be beneath the annual benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending
[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for a supplemental LAW grout facility will likely be beneath the annual benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget
[MOE: Ability to start and stop construction and operations in response to external factors.] – Very low likelihood of failure. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point
[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Operations, shipping, and disposal more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure
[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished]. (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to complete a grout facility by the project need date.

***3.3. Likelihood and consequences of failing to complete due to una*vailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable.

Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. Off-site disposal location could cease receipt of waste or permission to transport is revoked for unforeseen reasons. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been preselected, or if another disposal location must be identified. A ~2.5-month working inventory of material would remain onsite or in-transit until the issue is resolved (maximum of 750 containers).

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs (discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $3,414 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,108 M (includes commissioning)

4.2. Operations costs

$2,306 M (includes costs for transportation)

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.6 Selection Criteria Assessment for Alternative Grout 1C (Grout 1+Technetium/Iodine Removal)

Alternative Grout 1C: Single Supplemental Low-Activity Waste Grout Plant with Technetium/Iodine Removal and On-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – A large fraction of iodine does not have mobility to groundwater as it is removed from the supplemental LAW feed and moved offsite.

Uncertainty exists regarding the removal efficiency of other iodine species (iodate/organo-iodine) that may be disposed of in the primary waste form to IDF. Secondary waste form containing radionuclide assumed to be able to meet waste acceptance criteria for off-site disposal.

1.1.2.1.2. Technetium (confidence in non-pertechnetate will be evaluated below) – Removed from supplemental LAW by process. Secondary waste form containing radionuclide assumed to be able to meet waste acceptance criteria for off-site disposal. A large fraction of technetium does not have mobility to groundwater because it is removed from the supplemental LAW feed and moved offsite. Uncertainty exists regarding the removal efficiency of other technetium species (non-pertechnetate) that may be disposed of in the primary waste form to IDF.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3.1.3).

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Nitrate/nitrite mobility to groundwater is limited during the first 1,000 years compliance period. Retained only by diffusion barrier (physical entrapment). Recent diffusivity testing shows some formulations can retain nitrate/nitrate more effectively and estimate peak concentrations below the compliance standard. These tests were performed in a conservative, saturated environment, which would produce much greater release rates than actual unsaturated conditions in the IDF. Conservative assumptions regarding nitrate/nitrate subsurface behavior can result in projected exceedance of DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3).

1.1.2.3. Ammonia – No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; ammonia stripped during evaporation is immobilized at ETF.] Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from the LAW melter system so it is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Waste form has reduced conditions. Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be compliant.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form (grout redox chemistry).] – Cr(VI) sequestered by redox reactions with reductants in BFS and precipitation as hydroxide with alkali.

Uncertainty exists in rate of reoxidation of grout in IDF and change in waste form pH; an oxidized, neutral grout can exceed DWS for chromium. To limit mobility beyond the period of compliance chromium requires maintenance of reducing conditions for a portion of the waste form and maintain alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond period of compliance.

1.1.2.4.3. Other [No MOE needed] – Projected concentration of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS. Small volume of secondary waste compared to primary waste form as spent resin, loaded iodine columns, and equipment.

1.2. Long-term risks upon successful completion
[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – High confidence in speciation in waste and in the resulting waste form primarily as iodide with a fraction of iodate. Expect to dispose of immobilized iodine offsite in a suitable waste form. Fraction other iodine species may not be removed.

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in speciation in waste as pertechnetate with a fraction of non-pertechnetate. Expect to dispose of eluted immobilized technetium offsite in a suitable waste form (e.g., specialized grout).

1.2.2.3. ^{79}Se – Limited to no data available on the speciation in the waste, in grout, or mobility within grout waste forms. Limited attenuation in the Hanford subsurface. High confidence of minimal impact due to minimal inventory (144 Ci or ~2 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*).

1.2.2.4. Nitrates/nitrites – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are mobile in grout waste forms and will not be slowed without formulation modification. Nitrate and nitrite are a key constituent within the IDF, but will not drive waste classification or waste acceptance criteria. There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford tanks, and a recent assessment projected concentrations slightly above groundwater limits in the post-compliance period using a projection of a non-optimized grout waste form disposed of in IDF. As such, there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a performance assessment considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal impact.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – Very high confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation but low confidence in mercury speciation in tank waste. High confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface.

1.2.2.6.2. Chromium – High confidence in sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment, high confidence in knowledge of subsurface mobility; there is limited attenuation in the IDF backfill and subsurface although some mineral interactions (iron, carbonate, barium) have been observed. Chromate is slow moving in subsurface and expected to be compliant with DWS.

1.2.2.6.3. Other RCRA metals – Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage.] (See tank leak discussion in Volume I, Section 1.3.3 for more detail.) – Startup in ~13 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~13 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is more impactful because of dependence on cross site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction is near an operating radioactive facility (LAW Vitrification Facility); this single plant construction would be shorter duration in comparison to other alternatives.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (High consequence hazard is not applicable to this alternative since there is no vault.) Over 20 years of operation of Saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)] – Low risk. Large number of transports of raw materials onto site and waste form boxes onsite; no hazardous liquids shipped onsite; no rad liquid transport; off-site transport of radioactive materials (spent iodine media and technetium waste form).

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; all LAW/flush water during grouting is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[2]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater. Some flush solutions and, if not reused, technetium eluate evaporator condensate would be sent to LERF/ETF.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] –Minimal risk, few tanks and process unit operations. Only risk is transfers to evaporator and LERF/ETF.

[2] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills] – Low risk. Possible material transport truck/railcar accident of non-rad minimally hazardous dry solid ingredients. Possible accident during transport of secondary rad waste.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment].] – Very low volume. Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (480,000 gal per 1Mgal of waste). Estimate includes bounding additional 10% of the waste volume from flush solutions, resin regenerate solution, and evaporated eluate condensate (100,000 gal per 1 Mgal of waste) although most can be reused for elution. Spent ion exchange columns, equipment, spent iodine media, technetium waste form.

2.3.6. Greenhouse gas emissions

[MOE: Calculated fuel/power/deliveries.] At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~13 years

2.4.2. Duration to full capacity (additional years) 1 year

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues –Moderate risk. Minimal potential risk to delay operations except for development of iodine removal process; grout and technetium removal technologies are well understood and demonstrated successfully in DOE complex. Technetium waste form is untested but expected readily adaptable from existing methods. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*), but mitigation is to send non-compatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Low risk. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste.) [MOE: Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – Low-moderate risk of failure. The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, but engineering uncertainties are minimal.

Uncertainty remains in the removal of technetium/iodine and LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence of failure to identify a suitable iodine removal media or remedy results in failure in ability to dispose of onsite in IDF. Very high consequences.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Moderate likelihood of failure and moderate consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Technetium removal likely to be deployable. Fraction of non-pertechnetate and/or its behavior in grout may exceed estimated performance. Iodine removal may be impractical. Consequence: Cannot remove sufficient technetium and/or iodine from some portion of the feeds.

3.1.1.1.2. Suitable iodine removal media not identified so removal is inadequate/ Non-pertechnetate concentration is too high – Moderate likelihood that iodine removal method cannot be found and deployed. Very high likelihood that technetium removal process can be deployed successfully. Non-pertechnetate would be quantified in the characterization step so would be diverted to LAW vitrification. High consequences if amount of non-pertechnetate is too high or if iodine removal method cannot be found.

3.1.1.1.3. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility but impacts in process delays could occur. Low consequences.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species. Low consequences.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Moderate-low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Ion exchange for iodine is comparable to TSCR but with minimal dose; ion exchange for technetium is comparable to spherical resorcinol-formaldehyde (sRF) columns in WTP but with elution with warm water instead of acid. Consequence: Delayed processing, additional costs, missed milestones. Grout consequences mitigated by SRS operating experience providing input to operation and design and low operating cost per day; ion exchange is mature and simple technology.

3.1.1.2.1 Unit operations[3]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Iodine ion exchange columns – Comparable to TSCR but with minimal dose. Spent media may be sluiced out of the columns with water into a storage container.
- Technetium ion exchange columns – Comparable to TSCR, but with warm water elution and eluate evaporation, and water/caustic flushing of bed. Sluicing of spent resin to a disposal container (demonstrated at full scale).
- Technetium and iodine immobilization – TBD.
- Eluate evaporator – Simple small scale evaporator.
- Receipt tank (agitated, cooled?) – Vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.

[3] Very low or low complexity/consequences, unless specified otherwise.

- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container box disassembly and emplacement at IDF – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Measure pertechnetate/non-pertechnetate concentration. Monitor ^{99}Tc and ^{129}I in effluents during column processing; assume automated analyzers. Consequence: Reduced waste loading.
- Modeling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition. Moderate consequences.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Ion exchange columns are common. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (15 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on co-located processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple - Feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line is needed to support this alternative.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990) INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford tank waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Technetium ion exchange has been demonstrated multiple times with Hanford waste and simulants. Iodine ion removal has been tested only with Hanford simulants at lab scale. Consequence: Additional development time needed, delayed processing.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine ion exchanger is commercially available but only minimally tested but can be developed. Alternative substrate zeolite for iodine media may need to be developed to improve caustic resistance. Technetium ion exchanger is commercially available, but if conversion of non-pertechnetate is needed, this is untested. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Highly robust. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – Highly adaptable. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Proportion of iodide to iodate is variable and could limit effectiveness of iodine removal if iodate removal is less effective than iodide removal. Proportion of non-pertechnetate is unknown and could limit effectiveness of technetium removal. Consequence: More waste would be diverted to LAW vitrification. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for a supplemental LAW grout facility will likely be beneath the benchmark funding level for a supplemental LAW facility ($450M/yr).

3.2.2. Projected peak spending
[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Very low likelihood of failure. The peak funding needs for a supplemental LAW grout facility will likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget
[MOE: Ability to start and stop construction and operations in response to external factors.] – Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. Highly flexible. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point
[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Scenario is that operations more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure
[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to complete a grout facility by the project need date.

3.3. Likelihood and consequences of failing to complete due to unavailability of key services and materials

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises.

Technetium ion exchange media is available from a sole source U.S. company. Iodine media is presumed to be the commercially available material that was tested and is commercially available, but alternatives may need to be developed. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been preselected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $3,115 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,200 M (includes commissioning)

4.2. Operations costs

$1,915 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.7 Selection Criteria Assessment for Alternative Grout 1D

Alternative Grout 1D: Single Supplemental Low-Activity Waste Grout Plant with Technetium/Iodine Sample-and-Send with Off-site/On-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – Onsite: On-site inventory from supplemental LAW feed reduced by 50-70%. Iodine mobility to groundwater is limited during the first 1,000 years compliance period. Iodine sequestered by getter leads to enhanced retention in waste form; relative to non-getter waste form.

Projected ~100× below DWS (maximum contaminant level) per NDAA17 report but uncertainty in long-term performance with only laboratory data to date. Iodine not bound to getter can exceed DWS. To limit mobility beyond the period of compliance, iodine requires stability of getter phase to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout. Off-site portion: No impact to Hanford groundwater. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.1.2.1.2. Technetium (confidence in non-pertechnetate is evaluated below) – On-site inventory from supplemental LAW feed reduced by 50-70%. Technetium mobility to groundwater is limited during the first 1,000 years compliance period due to facility performance. BFS sequesters technetium providing high performance for technetium; ~10× below DWS per NDAA17 report; uncertainty in rate of reoxidation of grout in IDF; an oxidized grout can exceed DWS. To limit mobility beyond the period of compliance technetium requires maintenance of reducing conditions for a portion of the waste form during disposal to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout. Offsite: No impact to Hanford groundwater. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3.1.3). On-site inventory reduced by this alternative. Assuming high mobility from waste form release to subsurface is many orders of magnitude below conservative DWS. Offsite: No impact to Hanford groundwater. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE: Estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Onsite: Nitrate/nitrite mobility to groundwater is limited during the first 1,000 years compliance period. Retained only by diffusion barrier (physical entrapment). Recent diffusivity testing shows some formulations can retain nitrate/nitrate more effectively and estimate peak concentrations below the compliance standard. These tests were performed in a conservative, saturated environment, which would produce much greater release rates than actual unsaturated conditions in the IDF.

Conservative assumptions regarding nitrate/nitrate subsurface behavior can result in exceedance of DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3). On-site inventory reduced by this alternative in roughly the same fraction as the volume disposed.

Offsite: No impact to Hanford groundwater. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.3. Ammonia – Onsite: No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; ammonia stripped during evaporation is immobilized at ETF.] Ammonia from this option is low in the grouted secondary waste disposed of in IDF but ammonia will still be present from LAW melter system so is not differentiating among alternatives. Offsite: Minimal impact to Hanford groundwater due to grouted ETF solids. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements. Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Onsite: Waste form has reduced toxicity. Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be compliant. Offsite: Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Onsite: Sequestered by sulfide reaction with BFS. Offsite: Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.2. Chromium: [MOE is retention of chromium in waste form (grout redox chemistry).] – Onsite: Cr(VI) sequestered by redox reactions with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty exists in rate of reoxidation of grout in IDF and change in waste form pH; an oxidized, neutral grout can exceed DWS for chromium. To limit mobility beyond the period of compliance chromium requires maintenance of reducing conditions for a portion of the waste form and maintain alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond period of compliance. Offsite: Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.3. Other [No MOE needed] – Onsite: Projected concentration of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium. Offsite: Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.3. Total volume of primary and secondary waste forms – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS. Onsite: Total volume remaining onsite reduced by 30-60%. [MOE is volume of primary and all secondary waste forms.]

1.2. Long-term risks upon successful completion

[Exogenous risks (earthquake, catastrophic flood, volcano, etc.) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford/off-site environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity in the Hanford/off-site environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and in the resulting waste form as iodide with a fraction of iodate. Moderate confidence in the immobilization of AgI from reaction with getter in the waste form, but any unreacted free iodide/iodate is mobile. Success of the silver precipitation approach has been shown at the laboratory-scale using getters but not demonstrated at large scale.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

The immobile fractions as AgI can destabilize with time due to chemical reduction of Ag^{+} to Ag^{0} and competition with other species (e.g., sulfide which can form Ag_2S), the rate of these destabilization processes in the disposed waste form is untested. Iodine is a key constituent of interest in the IDF PA.

^{129}I can define waste classification but concentrations in Hanford tanks likely far lower than Class A limit[2]. Once released by chemical reactions and leached into the subsurface there is limited to no natural attenuation of iodide, and as such the supplemental LAW iodine inventory could impact groundwater in the post-compliance period. However, a complete assessment of any iodine impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior). Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.2. Technetium (including non-pertechnetates) – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste as pertechnetate with a fraction of non-pertechnetate. Within the waste form, there is high confidence in the conversion of pertechnetate to a reduced and insoluble technetium but there is an unknown behavior of non-pertechnetate. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form can be destabilized with time due to oxidation but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA. Technetium can define waste classification and select tanks have technetium concentrations that approach the Class A limit[3]. However, complete assessment of any technetium impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior). Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.3. ^{79}Se – Limited to no data available on the speciation in the waste, in grout, or mobility within grout waste forms. Limited attenuation in the Hanford subsurface. High confidence of minimal impact due to minimal inventory (144 Ci, or ~2 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*). Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

[2] ^{129}I is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

[3] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

1.2.2.4. Nitrates/nitrites – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are mobile in grout waste forms and will not be slowed without formulation modification. Nitrate and nitrite are a key constituent within the IDF but will not drive waste classification or waste acceptance criteria. There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford waste tanks, and a recent assessment projected concentrations slightly above groundwater limits in the post-compliance period using a projection of a non-optimized grout waste form disposed of in IDF.

As such there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior). Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.5. Ammonia/ammonium ion – Onsite: High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal impact. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – High confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation but low confidence in mercury speciation in tank waste. High confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface.

1.2.2.6.2. Chromium – High confidence in ability to pass TCLP due to sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment, high confidence in knowledge of subsurface mobility; there is limited attenuation in the IDF backfill and subsurface although some mineral interactions (iron, carbonate, barium) have been observed. Chromate is slow moving in subsurface and expected to be compliant with DWS.

1.2.2.6.3. Other RCRA metals – High confidence in ability to pass TCLP. Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP, however, if Ag is added as iodine getter, this adds uncertainty.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.3 for more detail.)] – Startup in ~13 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~13 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: no hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction is near an operating radioactive facility (LAW Vitrification Facility); this single plant construction would be shorter duration in comparison to other alternatives.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (High consequence hazard is not applicable to this alternative since there is no vault.) Over 20 years of operation of Saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: few trip/shipments to high number of shipments.)] – Moderate risk. Large number of transports of raw materials onto site and waste form boxes onsite; no hazardous liquids shipped onsite; no rad liquid transport. Onsite: No off-site transport of radioactive materials. Offsite: Many off-site transports of solid radioactive waste form packages to distant location(s). Practical impact will be negligible since transport of low dose solid radioactive materials is well known.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Low volume. Minimal; all LAW/flush water during grouting is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[4]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category.)] – Minimal risk, few tanks and process unit operations. Only risk is transfers to evaporator and LERF/ETF.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – Low risk. Possible material transport truck/railcar accident of non-rad minimally hazardous dry solid ingredients to Hanford site. Possible transport incidents of grouted waste form, but negligible release of radionuclides expected.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment.] – Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal waste).

2.3.6. Greenhouse gas emissions

[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426). Offsite: Expect shipments of ~23,000 grouted waste form boxes to distant disposal location(s).

[4] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~13 years

2.4.2. Duration to full capacity (additional years) 1 year

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delays

2.4.4.1. Delay due to technical/engineering issues – Low risk to delay operations due to grout technology; technology is well understood and demonstrated successfully at full-scale in the DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*). (Delays due to technical uncertainties contribute to increased cost risk and therefore potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk of delays. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste.) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – Low risk. The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, and getters will be included for on-site fraction, but engineering uncertainties are minimal. Uncertainty remains in the utility of getters at scale and LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence of failure to identify a suitable iodine getter or remedy results in shipping more waste offsite.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading.

3.1.1.1.2. Suitable getter (iodine and potentially technetium) not identified/long term performance inadequate – Medium likelihood and moderate consequence. While suitable getters for technetium and iodine have been tested in laboratory testing, the application of these getters in a production process and in conjunction with each other has not been demonstrated. Consequence of not identifying a suitable getter would be that on-site disposal of the grout is not permitted and other methods to sequester iodine are not identified. Mitigation is disposal offsite.

3.1.1.1.3. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping. Very low consequences.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP-LAW vitrification facility but impacts in process delays could occur. Low consequences.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[5]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – Vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment/load out station – Hoist and forklift operations.
- Container box disassembly and emplacement at IDF – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition. Moderate consequences.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-spec composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified.) Unit operations are sequential, easily decoupled, few feedback loops). Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites.

[5] Very low or low complexity/consequences, unless specified otherwise.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on collocated processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple - Feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line is needed to support this alternative.
- Rail line spur.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier. Offsite: Off-site disposal locations may need expansion.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Shipping grouted Hanford waste offsite successfully demonstrated during Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990) INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/ simulation and followed up with core sampling.

Adding iodine getters has not been demonstrated at scale. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford tank waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Consequence: Additional development time needed, delayed processing.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Highly robust. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] Low likelihood of failure. The funding needs for a supplemental LAW grout facility will likely be beneath the annual benchmark funding for a supplemental LAW facility ($450M/yr).

3.2.2. Projected peak spending
[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Very low likelihood of failure. The peak funding needs for a supplemental LAW grout facility will likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget
[MOE: Ability to start and stop construction and operations in response to external factors.] – Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. High flexibility. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point
[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Scenario is that operations, shipping, and disposal more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not start or stops until funding is available. Start of supplemental LAW mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to complete a grout facility by the project need date.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been pre-selected. Offsite: Off-site disposal location could cease receipt of waste or permission to transport is revoked for unforeseen reasons.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process. If the disposal location becomes unavailable, a ~2.5-month working inventory of material would remain onsite or in-transit until the issue is resolved (maximum of 750 containers).

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.) (Costs developed for alternative Grout 1B are shown below, since they are bounding [i.e., if 100% of the material needed to be shipped offsite.])

Total: $3.414 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,108 M (including commissioning costs)

4.2. Operations costs

$2,306 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.8 Selection Criteria Assessment for Alternative Grout 2A

Alternative Grout 2A: Separate Grout Plants for the 200 East and West Areas with On-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – Iodine mobility to ground water is limited during the first 1,000 years compliance period. Iodine sequestered by getter leads to enhanced retention in waste form relative to non-getter waste form.

Projected ~100× below DWS (maximum contaminant level) standard per NDAA17 report but uncertainty in long-term performance with only laboratory data to date. Iodine not bound to getter can exceed DWS. To limit mobility beyond the period of compliance, iodine requires stability of getter phase to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout.

1.1.2.1.2. Technetium (confidence in non-pertechnetate is evaluated below) [MOE will be projected concentration in groundwater.]– Technetium mobility to groundwater is limited during the first 1,000 years compliance period. BFS sequesters technetium providing high performance for technetium; ~10× below DWS per NDAA17 report; uncertainty in rate of reoxidation of grout in IDF; an oxidized grout can exceed DWS. To limit mobility beyond the period of compliance technetium requires maintenance of reducing conditions for a portion of the waste form during disposal to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci; see Volume II, Section E.3.1.3). Expect comparable leachability to nitrate; assuming high mobility from waste form release to subsurface is many orders of magnitude below conservative DWS.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE: Estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Nitrate/nitrite mobility to groundwater is limited during the first 1,000 years compliance period. Retained only by diffusion barrier (physical entrapment). Recent diffusivity testing shows some formulations can retain nitrate/nitrate more effectively and estimate peak concentrations below the compliance standard. These tests were performed in a conservative, saturated environment, which would produce much greater release rates than actual unsaturated conditions in the IDF. Conservative assumptions regarding nitrate/nitrate subsurface behavior can result in exceedance of DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3).

1.1.2.3. Ammonia – No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; ammonia stripped during evaporation is immobilized at ETF.] – Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Waste form has reduced conditions. Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be compliant.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS.

1.1.2.4.2. Chromium – Cr(VI) sequestered by redox reaction with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty exists in rate of reoxidation of grout in IDF and change in waste form pH; an oxidized, neutral grout can exceed DWS for chromium. To limit mobility beyond the period of compliance, chromium requires maintenance of reducing conditions for a portion of the waste form and maintaining alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond period of compliance. [MOE is retention of chromium in waste form (grout redox chemistry).]

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium.

1.1.3. Total volume of primary and secondary waste forms – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS. [MOE is volume of primary and all secondary waste forms.]

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and in the resulting waste form as iodide with a fraction of iodate. Moderate confidence in the immobilization of AgI from reaction with getter in the waste form, but any unreacted free iodide/iodate is mobile. Success of the silver precipitation approach has been shown at the laboratory-scale using getters but not demonstrated at large scale. The immobile fractions as AgI can destabilize with time due to chemical reduction of Ag^{+} to Ag^{0} and competition with other species (e.g., sulfide, which can form Ag_2S), the rate of these destabilization processes in the disposed waste form is untested. Iodine is a key constituent of interest in the IDF PA. ^{129}I can define waste classification but concentrations in Hanford waste tanks likely far lower than Class A limit[2]. Once released by chemical reactions and leached into the subsurface there is limited to no natural attenuation of iodide, and as such the supplemental LAW iodine inventory could impact groundwater in the post-compliance period. However, a complete assessment of any iodine impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste as pertechnetate with a fraction of non-pertechnetate. Within the waste form, there is high confidence in the conversion of pertechnetate to a reduced and insoluble technetium, but there is an unknown behavior of non-pertechnetate. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form can be destabilized with time due to oxidation, but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA. Technetium can define waste classification and select tanks have technetium concentrations that approach the Class A limit[3]. However, complete assessment of any technetium impact in the post-compliance period must be evaluated in a performance assessment considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

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[2] ^{129}I is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

[3] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

1.2.2.3. ^{79}Se – Limited to no data available on the speciation in the waste, in grout, or mobility within grout waste forms. Limited attenuation in the Hanford subsurface. High confidence of minimal impact due to minimal inventory (144 Ci or ~2 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*).

1.2.2.4. Nitrates/nitrites – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are mobile in grout waste forms and will not be slowed without formulation modification. Nitrate and nitrite are a key constituent within the IDF, but will not drive waste classification or waste acceptance criteria. There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford waste tanks, and a recent assessment projected concentrations slightly above groundwater limits in the post-compliance period using a projection of a non-optimized grout waste form disposed of in IDF. As such there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a performance assessment considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal impact.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – Very high confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation but low confidence in mercury speciation in tank waste. High confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface.

1.2.2.6.2. Chromium – High confidence in sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment, high confidence in knowledge of subsurface mobility; there is limited attenuation in the IDF backfill and subsurface although some mineral interactions (iron, carbonate, barium) have been observed. Chromate is slow moving in subsurface and expected to be compliant with DWS.

1.2.2.6.3. Other RCRA metals –Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP; however, if Ag is added as iodine getter, this adds uncertainty.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.3 for more detail.)] – Startup in ~13 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~13 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is less impactful because of no dependence on cross-site transfer line, less specific feed piping, and tank utilization, etc. Since this involves both 200 East and West Area facilities, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: no hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction of the 200 East plant is near an operating radioactive facility (LAW Vitrification Facility); the smaller 200 West plant construction would be shorter duration in comparison to the 200 East plant.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Slight increase in risk due to additional handling/ truck loading. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426).

(High consequence hazard is not applicable to this alternative since there is no vault.) Over 20 years of operation of Saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)] – Low risk. Large number of transports of raw materials onto site and waste form boxes onsite; no hazardous liquids shipped onsite; no off-site transport of radioactive materials. Relative to alternative Grout 1, cross-site transfer of supernatant liquid from 200 West to 200 East would be eliminated or reduced; but evaporator residue would need to be transported by truck to LERF/ETF.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; all LAW/flush water during grouting is recycled into next batch; evaporator condensate collected (and transported, for 200 West tanks) to LERF/ETF (~38% of feed volume[4]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal supplemental LAW. Negligible particulates from dry feed additions [per RPP-RPT-63426].

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Moderate risk. Transport of secondary waste to LERF/ETF increases risk; decreased necessity of west to east cross site transfer of supernatant liquid reduces risk.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – Negligible risk. Only possible is material transport truck/railcar accident of non-rad minimally hazardous dry solid ingredients.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment].] – Very low volume. Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal waste).

[4] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.3.6. Greenhouse gas emissions
[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) – For 200 East plant, ~13 years for a full capacity plant (determined because of budget line item). For 200 West plant, additional 3-5 years (assumed part of same budget line item).

2.4.2. Duration to full capacity (additional years) 1 year

2.4.3. Duration of operations (additional years) as needed to support HLW; 200 West plant may be able to cease operations early.

2.4.4. Risk of additional mission delay

2.4.4.1. Delays due to technical/engineering issues – For 200 East plant, minimal risk to delay operations; technology is well understood and demonstrated successfully at full scale in DOE complex. For 200 West plant, modular systems of higher complexity have been deployed. Grout technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*), and mitigation is to send non-compatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion
(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste.) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, and getters will be included, but engineering uncertainties are minimal. Uncertainty remains in the utility of getters at scale and LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Low risk of failure. Consequence of failure to identify a suitable iodine getter or remedy results in failure in ability to dispose of waste onsite in IDF. Very high consequences.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading.

3.1.1.1.2. Suitable getter (iodine and potentially technetium) not identified/long term performance inadequate – Medium likelihood and high consequence. While suitable getters for technetium and iodine have been tested in laboratory testing, the application of these getters in a production process and in conjunction with each other has not been demonstrated. Consequence of not identifying a suitable getter would be that on-site disposal of the grout is not permitted and other methods to sequester iodine are not identified. Very high consequences.

3.1.1.1.3. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping. Leaks of cross site transfer line leaks is reduced. Very low consequences.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility, but impacts in process delays could occur. Low consequences.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk – The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – (Low complexity) Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release.

Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[5]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – Vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container box disassembly and emplacement at IDF – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition (moderate complexity).
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

[5] Very low or low complexity/consequences, unless specified otherwise

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites). The addition of a west grout facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduces SST leakage risk; reduce cross-site transfer of supernatant liquid.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on collocated processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple - Feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line is not needed to support this alternative.
- Minimal additional risk from more construction.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: completely ready to requiring development to make process work] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990) INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Adding iodine getters has not been demonstrated at scale. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS, but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Consequence: Additional development time needed, delayed processing.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Highly robust. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Availability of two grout plants further facilitates upgrades without delaying mission. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for a supplemental LAW grout facility will likely be beneath the annual benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending
[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for a supplemental LAW grout facility will likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget
[MOE: Ability to start and stop construction and operations in response to external factors.] – Very low likelihood of failure. Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) Very low likelihood of failure.

Scenario is that operations are more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to complete a grout facility by the project need date.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been pre-selected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $3,395M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,544 M (includes commissioning)

4.2. Operations costs

$1,851 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.9 Selection Criteria Assessment for Alternative Grout 2B

Alternative Grout 2B: Separate Grout Plants for the 200 East and West Areas with Off-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen); however, off-site disposal sites do not have a pathway to potable water due to their geology.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – High residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.2.1.2. Technetium (confidence in non-pertechnetate is evaluated below) [MOE will be projected concentration in groundwater.] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form – Minimal impact due to limited quantity (114 Ci total in tank farms per RPP—ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*). No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.2.3. Ammonia – No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; no differences between alternatives; ammonia stripped during evaporation immobilized at ETF.] – Minimal impact to Hanford groundwater due to grouted ETF solids. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site. Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be TCLP compliant (RCRA).

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory. Grout waste form will pass TCLP (RCRA).

1.1.2.4.2. Chromium – Cr(VI) sequestered by redox reaction with reductants in BFS and precipitation as hydroxide with alkali. [MOE is retention of chromium in waste form (grout redox chemistry).] Grout waste form will pass TCLP (RCRA).

1.1.2.4.3. Other [No MOE needed.] – Grout waste form will pass TCLP (RCRA).

1.1.3. Total volume of primary and secondary waste forms [MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS.

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics (uncertainty with the concentration of LDR organics in the waste) – High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity in the Hanford environment.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.2.2.2. Technetium (including non-pertechnetates) – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.2.2.3. ^{79}Se – High confidence of minimal impact due to minimal inventory (144 Ci or ~1 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*). Despite limited to no data available on the speciation in the waste, in grout, or mobility within grout waste forms, there is high confidence of minimal inventory. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.2.2.4. Nitrates/nitrites – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – High confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.2. Chromium – High confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.3. Other RCRA metals –High confidence in ability to pass TCLP/waste acceptance criteria. Moderate confidence on speciation in Hanford waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.3 for more detail.)] – Startup in ~13 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks.

Startup of this process in ~13 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is less impactful because of no dependence on cross site transfer line, less specific feed piping, and tank utilization, etc. Since this involves both 200 East and West Area facilities, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description).

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction of the 200 East plant is near an operating radioactive facility (LAW Vitrification Facility); the smaller 200 West plant construction would be shorter duration in comparison to the 200 East plant.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (High consequence hazard is not applicable to this alternative since there is no vault.) Over 20 years of operation of Saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)] – Moderate risk. Large number of transports of raw materials onto site and waste form boxes onsite; evaporator condensate will be shipped from west to LERF/ETF (by truck); many off-site transports of solid radioactive waste form packages to distant location(s). Transport of low dose radioactive materials is well known.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; all LAW/flush water is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[2]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Moderate risk. Transport of secondary waste to LERF/ETF increases risk; decreased necessity of west to east cross site transfer of supernate reduces risk.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – Low risk. Possible material transport truck/railcar accident of non-rad minimally hazardous dry solid ingredients to Hanford Site. Possible transport incidents of grouted waste form, but negligible release of radionuclides expected.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment).] – Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal waste).

[2] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+]

2.3.6. Greenhouse gas emissions
[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426). Expect shipments of ~46,000 grouted waste form boxes to distant disposal location(s). (See Volume II, Section H.9 for more information.)

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~13 years for a full capacity plant (determined because of budget line item). For 200 West plant, additional 3-5 years (assumed part of same budget line item).

2.4.2. Duration to full capacity (additional years) 1 year

2.4.3. Duration of operations (additional years) as needed to support HLW. 200 West plant may be able to cease operations early. TBD.

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues – Low risk. For east plant, minimal risk to delay operations; 200 East plant technology is well understood and demonstrated successfully at full scale in DOE complex. For 200 West plant, modular systems of higher complexity have been deployed. Grout technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*). Mitigation is to send non-compatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk of delay. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion
(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste.) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences; first is likelihood, then consequences.] – Low risk. The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, but engineering uncertainties are minimal. Uncertainty remains in LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. The grout alternative will use the same flowsheet and approach as the existing SRS facility. Consequence is reduced waste loading or diverting more waste to LAW melters.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading.

3.1.1.1.2. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping. Leaks of cross site transfer line leaks is reduced.

3.1.1.1.3. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed enough to be below regulatory limit if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidization methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility but impacts in process delays could occur.

3.1.1.1.4. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – L ow complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[3]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – CSTR vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch Mixer/Container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations; train.
- Container box disassembly and emplacement at -off-site location(s) – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modeling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition. Moderate complexity.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

[3] Very low or low complexity/consequences, unless specified otherwise

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites. The addition of a 200 West grout facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduces SST leakage risk; reduce cross-site transfer of supernatant liquid.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on collocated processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line is not needed to support this alternative.
- Minimal additional risk from more construction.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier. Off-site disposal locations may need expansion.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Shipping grouted Hanford waste offsite successfully demonstrated during Test Bed Initiative. Grout in general is demonstrated; saltstone facilities at SRS (similar process, scale, and waste operations since 1990) INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/ simulation and followed up with core sampling. Adding iodine getters has not been demonstrated at scale. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Consequence: Additional development time needed, delayed processing. Moderate consequences.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed.

Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Very high robustness. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative. Low consequences.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for a supplemental LAW grout facility will likely be beneath the benchmark funding levels for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending
[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Very low likelihood of failure. The peak funding needs for a supplemental LAW grout facility will likely be beneath the benchmark funding levels for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget
[MOE: Ability to start and stop construction and operations in response to external factors.] – Very high flexibility. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point
[MOE: Failure not likely until end of mission to failure likely prior to start of processing.]

(Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) - Scenario is operations, shipping, and disposal more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to complete a grout facility by the project need date.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier, but alternates could be developed, qualified, and readied for deployment to substitute if the need arises.

Off-site disposal location could cease receipt of waste or permission to transport is revoked for unforeseen reasons. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been pre-selected, or if another disposal location must be identified. A ~2.5-month working inventory of material would remain onsite or in-transit until the issue is resolved (maximum of 750 containers).

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water, and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $4,318 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,544 M (includes commissioning costs)

4.2. Operations costs

$2,774 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.10 Selection Criteria Assessment for Alternative Grout 2C

Alternative Grout 2C: Separate Grout Plants for the 200 East and West Areas with Technetium/Iodine Removal and On-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – A large fraction of iodine does not have mobility to groundwater as it is removed from the supplemental LAW feed and moved offsite. Uncertainty exists regarding the removal efficiency of other iodine species (iodate/organo-iodine) that may be disposed of in the primary waste form to IDF.

Secondary waste form containing radionuclide assumed to be able to meet waste acceptance criteria for off-site disposal.

1.1.2.1.2. Technetium (confidence in non-pertechnetate is evaluated below) – Removed from supplemental LAW by process. Secondary waste form containing radionuclide assumed to be able to meet waste acceptance criteria for off-site disposal. A large fraction of technetium does not have mobility to groundwater because it is removed from the supplemental LAW feed and moved offsite. Uncertainty exists regarding the removal efficiency of other technetium species (non-pertechnetate) that may be disposed of in the primary waste form to IDF.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci; see Volume II, Section E.3).

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Nitrate/nitrite mobility to groundwater is limited during the first 1,000 years compliance period. Retained only by diffusion barrier (physical entrapment). Recent diffusivity testing shows some formulations can retain nitrate/nitrate more effectively and estimate peak concentrations below the compliance standard. These tests were performed in a conservative, saturated environment, which would produce much greater release rates than actual unsaturated conditions in the IDF. Conservative assumptions regarding nitrate/nitrate subsurface behavior can result in projected exceedance of DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3).

1.1.2.3. Ammonia – No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; ammonia stripped during evaporation is immobilized at ETF.] Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Waste form has reduced conditions. Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be compliant.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form (grout redox chemistry).] – Cr(VI) sequestered by redox reaction with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty exists in rate of reoxidation of grout in IDF and change in waste form pH; an oxidized, neutral grout can exceed DWS for chromium.

To limit mobility beyond the period of compliance, chromium requires maintenance of reducing conditions for a portion of the waste form and maintaining alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond period of compliance.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium.

1.1.3. Total volume of primary and secondary waste forms [MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS. Small volume of secondary waste compared to primary waste form as spent resin, loaded iodine columns, and equipment.

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – High confidence in speciation in waste and in the resulting waste form primarily as iodide with a fraction of iodate. Expect to dispose immobilized iodine offsite in a suitable waste form. Fraction present as other iodine species may not be removed.

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in speciation in waste as pertechnetate with a fraction of non-pertechnetate. Expect to dispose eluted immobilized technetium offsite in a suitable waste form (e.g., specialized grout).

1.2.2.3. ^{79}Se – Limited to no data available on the speciation in the waste, in grout, or mobility within grout waste forms. Limited attenuation in the Hanford subsurface. High confidence of minimal impact due to minimal inventory (144 Ci or ~2 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*).

1.2.2.4. Nitrates/nitrites – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are mobile in grout waste forms and will not be slowed without formulation modification. Nitrate and nitrite are a key constituent within the IDF, but will not drive waste classification or waste acceptance criteria. There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford tanks, and a recent assessment projected concentrations slightly above groundwater limits in the post-compliance period using a projection of a non-optimized grout waste form disposed of in IDF. As such, there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior).

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal impact.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – Very high confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation, but low confidence in mercury speciation in tank waste. High confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface.

1.2.2.6.2. Chromium – High confidence in sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment, high confidence in knowledge of subsurface mobility; there is limited attenuation in the IDF backfill and subsurface although some mineral interactions (iron, carbonate, barium) have been observed. Chromate is slow moving in subsurface and expected to be compliant with DWS.

1.2.2.6.3. Other RCRA metals – Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.3 for more detail.)] – Startup in ~13 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~13 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is less impactful because it does not rely on the cross-site transfer line, and is more flexible in specific feed piping, tank utilization, etc. Since this involves both 200 West and 200 East Area facilities, it is less directly dependent on specific infrastructure, including DSTs, and would therefore be less impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction of the 200 East plant is near an operating radioactive facility (LAW Vitrification Facility); the smaller 200 West plant construction would be shorter duration in comparison to the 200 East plant.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Slight increase in risk due to additional handling/truck loading. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (High consequence hazard is not applicable to this alternative since there is no vault). Over 20 years of operation of Saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)] – Low risk. Large number of transports of raw materials onto site and waste form boxes onsite; no hazardous liquids shipped onsite; no off-site transport of radioactive materials. Relative to alternative Grout 1A/B/C, cross-site transfer of supernatant liquid from 200 West to 200 East would be eliminated or reduced; but evaporator residue would need to be transported by truck to LERF/ETF.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; all LAW/flush water during grouting is recycled into next batch; evaporator condensate collected (and transported, for 200 West tanks) to LERF/ETF (~38% of feed volume[2]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Moderate risk. Transport of secondary waste to LERF/ETF increases risk; decreased necessity of west to east cross-site transfer of supernatant liquid reduces risk.

[2] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+]

2.3.4. Off-site transportation spills
[MOE: No risk of off-site spills to high risk for off-site spills.] – Moderate risk. Possible material transport truck/railcar accident of non-rad minimally hazardous dry solid ingredients. Possible accident during transport of secondary rad waste.

2.3.5. Secondary waste streams generated
[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment).] – Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (480,000 gal per 1 Mgal waste). Estimate includes bounding additional 10% of the waste volume from flush solutions, resin regenerate solution, and evaporated eluate condensate (100,000 gal per 1 Mgal waste) although most can be reused for elution. Spent ion exchange columns, equipment, spent iodine media, technetium waste form.

2.3.6. Greenhouse gas emissions
[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) for 200 East plant, ~13 years for a full capacity plant (determined because of budget line item). For 200 West plant, additional 3-5 years (assumed part of same budget line item).

2.4.2. Duration to full capacity (additional years) 1 year

2.4.3. Duration of operations (additional years) as needed to support HLW; 200 West plant may be able to cease operations early. TBD.

2.4.4. Risk of additional mission delays

2.4.4.1. Delay due to technical/engineering issues – Moderate risk. For 200 East plant, minimal risk to delay operations; except for development of iodine removal process; grout and technetium removal technologies are well understood and demonstrated successfully at full scale in DOE complex. For 200 West plant, modular systems of higher complexity have been deployed. Grout technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*), but mitigation is to send noncompatible wastes to the LAW melter. Technetium waste form is untested but expected readily adaptable from existing methods. LDR removal has had only limited testing but mitigation is to send noncompatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Low risk. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste.) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – Low-moderate risk of failure. The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, but engineering uncertainties are minimal. Uncertainty remains in the removal of technetium/iodine and LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence of failure to identify a suitable iodine removal media or remedy results in failure in ability to dispose of waste onsite in IDF. Very high consequences.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Moderate likelihood of failure and moderate consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Technetium removal likely to be deployable. Fraction of non-pertechnetate and/or its behavior in grout may exceed estimated performance. Iodine removal may be impractical. Consequence: Cannot remove sufficient technetium and/or iodine from some portion of the feeds.

3.1.1.1.2. Suitable iodine removal media not identified/non-pertechnetate concentration is too high – Moderate likelihood that iodine removal method cannot be found and deployed. Very high likelihood that technetium removal process can be deployed successfully. Non-pertechnetate would be quantified in the characterization step so would be diverted to LAW vitrification.

3.1.1.1.3. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping. Leaks of cross site transfer line leaks is reduced.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods.

Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility, but impacts in process delays could occur. Low consequences.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species. Low consequences.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Moderate-low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Ion exchange for iodine is comparable to TSCR but with minimal dose; Ion exchange for technetium is comparable to sRF columns in WTP but with elution with warm water instead of acid. Consequence: Delayed processing, additional costs, missed milestones. Grout consequences mitigated by SRS operating experience providing input to operation and design and low operating cost per day; ion exchange is mature and simple technology.

3.1.1.2.1 Unit operations [3]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Iodine ion exchange columns – Comparable to TSCR but with minimal dose. Spent media may be sluiced out of the columns with water into a storage container.
- Technetium ion exchange columns – Comparable to TSCR, but with warm water elution and eluate evaporation, and water/caustic flushing of bed. Sluicing of spent resin to a disposal container (demonstrated at full scale).
- Technetium and Iodine immobilization – TBD.
- Eluate evaporator – Simple small scale evaporator.

[3] Very low or low complexity/consequences, unless specified otherwise.

- Receipt tank (agitated, cooled?) – Vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container box disassembly and emplacement at IDF – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modeling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (15 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites. The addition of a 200 West grout facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduces SST leakage risk; reduce cross-site transfer of supernatant. liquid

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on collocated processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple - feed line to facility all that is needed except for feeds with LDR organics that require diversion.

- Cross-site supernatant liquid transfer line is not needed to support this alternative.
- Minimal additional risk from more construction.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier.

3.1.1.5. Technology maturity, including Test Bed Initiative [MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990) INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Technetium ion exchange has been demonstrated multiple times with Hanford waste and simulants. Iodine ion removal has been tested only with Hanford simulants at lab scale. Consequence: Additional development time needed, delayed processing.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed. Alternative substrate zeolite for iodine media may need to be developed to improve caustic resistance. Technetium ion exchanger is commercially available, but if conversion of non-pertechnetate is needed, this is untested. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Highly robust. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions

[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – Highly adaptable. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Proportion of iodide to iodate is variable and could limit effectiveness of iodine removal if the sorbent only removes iodide. Proportion of non-pertechnetate is unknown and could limit effectiveness of technetium removal. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)

[MOE: Easily incorporated to impossible.] – Highly adaptable. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Availability of two grout plants further facilitates upgrades without delaying mission. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending

[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for a supplemental LAW grout facility will likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for a supplemental LAW grout facility will likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – Highly flexible. Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Scenario is that operations are more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to complete a grout facility by the project need date.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier, but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. Technetium ion exchange media is available from a sole source U.S. company. Iodine media is presumed to be the commercially available material that was tested and is commercially available, but alternatives may need to be developed. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been preselected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water, and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $3,847 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,636 M (includes commissioning)

4.2. Operations costs at Hanford

$2.211 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.11 Selection Criteria Assessment for Alternative Grout 4A

Alternative Grout 4A: Off-site Vendor for Grouting with On-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

Note: This evaluation assumes that the vendor performs the grouting process and adds the getters for iodine (i.e., it is essentially identical to Grout 1A alternative in operations and product, and only differs in location of the immobilization step).

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vit. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – Iodine mobility to ground water is limited during the first 1,000 years compliance period. Iodine sequestered by getter leads to enhanced retention in waste form; relative to non-getter waste form. Projected ~100x below DWS (maximum contaminant level) per NDAA17 report but uncertainty in long-term performance with only laboratory data to date. Iodine not bound to getter can exceed DWS. To limit mobility beyond the period of compliance, iodine requires stability of getter phase to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout.

1.1.2.1.2. Technetium (confidence in non-pertechnetate is evaluated below) – Technetium mobility to groundwater is limited during the first 1,000 years compliance period due to facility performance. BFS sequesters technetium providing high performance for technetium; ~10× below DWS per NDAA17 report; uncertainty in rate of reoxidation of grout in IDF; an oxidized grout can exceed DWS. To limit mobility beyond the period of compliance technetium requires maintenance of reducing conditions for a portion of the waste form during disposal to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3). Assuming high mobility from waste form release to subsurface is many orders of magnitude below conservative DWS.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Nitrate/nitrite mobility to groundwater is limited during the first 1,000 years compliance period. Retained only by diffusion barrier (physical entrapment). Recent diffusivity testing shows some formulations can retain nitrate/nitrate more effectively and estimate peak concentrations below the compliance standard. These tests were performed in a conservative, saturated environment, which would produce much greater release rates than actual unsaturated conditions in the IDF. Conservative assumptions regarding nitrate/nitrate subsurface behavior can result in exceedance of DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3).

1.1.2.3. Ammonia – No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; no differences between alternatives; ammonia stripped during evaporation is immobilized at ETF.] Ammonia from this option is low in the grouted secondary waste disposed in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Waste form has reduced toxicity. Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be compliant.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form (grout redox chemistry).] – Cr(VI) sequestered by redox reaction with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty exists in rate of reoxidation of grout in IDF and change in waste form pH; an oxidized, neutral grout can exceed DWS for chromium. To limit mobility beyond the period of compliance chromium requires maintenance of reducing conditions for a portion of the waste form and maintain alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond period of compliance.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium.

1.1.3. Total volume of primary and secondary waste forms [MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed at SALDS.

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and in the resulting waste form as iodide with a fraction of iodate. Moderate confidence in the immobilization of AgI from reaction with getter in the waste form, but any unreacted free iodide/iodate is mobile. Success of the silver precipitation approach has been shown at the laboratory scale using getters but not demonstrated at large scale. The immobile fractions as AgI can destabilize with time due to chemical reduction of Ag^{+} to Ag^{0} and competition with other species (e.g., sulfide, which can form Ag_2S), the rate of these destabilization processes in the disposed waste form is untested. Iodine is a key constituent of interest in the IDF PA. ^{129}I can define waste classification, but concentrations in Hanford tanks likely far lower than Class A limit[2]. Once released by chemical reactions and leached into the subsurface there is limited to no natural attenuation of iodide, and as such the supplemental LAW iodine inventory could impact groundwater in the post-compliance period. However, a complete assessment of any iodine impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste as pertechnetate with a fraction of non-pertechnetate. Within the waste form, there is high confidence in the conversion of pertechnetate to a reduced and insoluble technetium, but there is an unknown behavior of non-pertechnetate. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form can be destabilized with time due to oxidation, but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA. Technetium can define waste classification and select tanks have technetium concentrations that approach the Class A limit[3]. Once in the subsurface there is limited to no natural attenuation of technetium, and as such the supplemental LAW technetium inventory could impact groundwater compliance limit.

[2] ^{129}I is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

[3] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

However, a complete assessment of any technetium impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.3. ^{79}Se – Expect to remain soluble in grout; retained by diffusion barrier. High confidence of minimal impact due to minimal inventory (144 Ci or ~1 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*).

1.2.2.4. Nitrates/nitrites – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are mobile in grout waste forms and will not be slowed without formulation modification. Nitrate and nitrite are a key constituent within the IDF, but will not drive waste classification or waste acceptance criteria. There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford tanks, and a recent assessment projected concentrations slightly above groundwater limits in the post-compliance using a projection of a non-optimized grout waste form disposed in IDF. As such there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. Small amount of ammonia in ETF secondary waste grout disposed in IDF poses minimal impact.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – High confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation, but low confidence in mercury speciation in tank waste. High confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface.

1.2.2.6.2. Chromium – High confidence in sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment, high confidence in knowledge of subsurface mobility; there is limited attenuation in the IDF backfill and subsurface although some mineral interactions (iron, carbonate, barium) have been observed. Chromate is slow moving in subsurface and expected to be compliant with DWS.

1.2.2.6.3. Other RCRA metals – Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria. Some species may have natural attenuation in the subsurface.

Based on data to date, waste form is likely to pass TCLP; however, if Ag is added as iodine getter, this adds uncertainty.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.3 for more detail.)] – Startup in ~5 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~5 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is less impactful because it does not rely on the cross-site transfer line, and is more flexible in specific feed piping, tank utilization, etc. Since this involves both a 200 West and 200 East Area facilities, it is less directly dependent on specific infrastructure, including DSTs, and would therefore be less impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. No construction near an operating radioactive facility. Some worker exposure to radioactive liquids due to loading/unloading liquid in truck.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426).

(High consequence hazard is not applicable to this alternative since there is no vault.) Over 20 years of operation of Saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)] – High risk. No transports of raw materials onto site; no hazardous liquid chemicals shipped onsite; many rad liquid transports of decontaminated supplemental LAW to offsite; rad liquid transport of evaporator condensate to ETF (assumed to be by truck); many off-site transports of solid radioactive materials (grouted waste) from vendor to onsite.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to high discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; evaporator condensate collected to LERF/ETF (~38% of feed volume[4]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Moderate risk. Few tanks and process unit operations onsite. Risk of liquid spills during transport of both supplemental LAW to off-site vendor and evaporator condensate to LERF/ETF. Mitigated by experience with shipment of radioactive liquids.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – Moderate risk. Risk of liquid spills during transport of liquid decontaminated supplemental LAW to off-site vendor.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment].] – Minimal solid waste; some equipment and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal of waste).

[4] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.3.6. Greenhouse gas emissions
[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals, assuming that the vendor requires the same amount of electricity and grout formers as was calculated for alternative Grout 1A (RPP-RPT-63426). There would be additional emissions from transport of the liquid to the vendor and return of the grouted waste form to onsite.

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~5 years. Vendors are available with the ability to perform this operation with existing facilities. Time to startup will be a function of the readiness of the Hanford Site to ship material to the vendor and the permitting required to process and dispose of the waste.

2.4.2. Time to full capacity (additional years) 0 years.- Vendors are available with the ability to perform this operation with existing facilities.

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delays

2.4.4.1. Delays due to technical/engineering issues – Minimal risk to delay operations; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*), but mitigation is to send non-compatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste.) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, and getters will be included, but engineering uncertainties are minimal. Uncertainty remains in the utility of getters at scale and LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence of failure to identify a suitable iodine getter or remedy results in failure in ability to dispose of waste onsite in IDF. Very high consequences.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading.

3.1.1.1.2. Suitable getter (iodine and potentially technetium) not identified/long-term performance inadequate – Medium likelihood and high consequence. While suitable getters for technetium and iodine have been tested in laboratory testing, the application of these getters in a production process and in conjunction with each other has not been demonstrated. Consequence of not identifying a suitable getter would be that on-site disposal of the grout is not permitted and other methods to sequester iodine are not identified.

3.1.1.1.3. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping. Very low consequences.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidization methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility, but impacts in process delays could occur. Mitigation is potential for off-site vendor treatment.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Consequence: Concentration of organics critical for assessing waste acceptance criteria; analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations.

The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[5]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator Condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt/storage tank (agitated, cooled?) – Vessel with pumps.
- Receipt tank (agitated, cooled?) – CSTR vessel with pumps.
- Silos (4) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch Mixer/Container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container receipt – Hoist and forklift operations.
- Container box disassembly and emplacement at IDF – Forklift and crane operations.

Note: Other operations are responsibility of the vendor and are not considered here.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modeling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition. Moderate complexity.
    - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

[5] Very low or low complexity/consequences, unless specified otherwise

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites. The use of an off-site grouting facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduces SST leakage risk; reduce cross-site transfer of supernatant liquid.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – only building TFPT/LDR evaporator and liquid load-out facility onsite.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple - feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line may not be needed to support this alternative assuming a 200 West area location.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed.

3.1.1.5. Technology maturity, including Test Bed Initiative [MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990) INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Adding iodine getters has not been demonstrated at scale. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Alternative assumes that vendor can produce viable waste form. Consequence: Additional development time needed, delayed processing.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Very high robustness. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative. Low consequences.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible] – Highly adaptable. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for off-site immobilization will likely be beneath the annual budget benchmark for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending
[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for off-site immobilization will likely be beneath the annual budget benchmark for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget
[MOE: Ability to start and stop construction and operations in response to external factors.] – Very flexible. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] – Very low likelihood of failure. Scenario is that operations more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Operation does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to perform this alternative by the project need date.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier, but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. If the vendor is unable to perform the task, another vendor could be selected. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been preselected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $3,338 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$411 M (includes commissioning costs)

4.2. Operations costs

$2,927 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.12 Selection Criteria Assessment for Alternative Grout 4B

Alternative Grout 4B: Off-site Vendor for Grouting with Off-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

Note: This evaluation assumes that the vendor performs the grouting process (i.e., it is essentially identical to Grout 1B alternative in operations and product, and only differs in location of the immobilization step).

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents – to all retained–to–amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over the long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for the long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for the long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.1.2. Technetium (non-pertechnetate will be evaluated below in confidence) [MOE is projected concentration in groundwater.] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site. BFS sequesters technetium.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3.1.3). No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection.] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives; ammonia stripped during evaporation is immobilized at ETF.] – Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives. No significant amount of residual ammonia in grouted tank wastes. Minimal impact to Hanford groundwater due to grouted ETF solids from on-site supplemental LAW evaporator. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements. Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be TCLP compliant (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory. Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.2. Chromium – Cr(VI) sequestered by redox reductants in BFS and precipitation as hydroxide with alkali. Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.3. Other [No MOE needed.] – Grout waste form will be TCLP-compliant (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include the evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS.

1.2. Long-term risks upon successful completion
[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentrations of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed (RPP-RPT-64064, *Distribution of LDR Organic Compounds in Hanford Tanks Waste and the Implications to LAW Treatment by Cementitious Solidification/Stabilization*); additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in speciation in waste as predominantly pertechnetate with a small fraction of non-pertechnetate in most tanks. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.3. ^{79}Se – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.4. Nitrates/nitrites – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – High confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.2. Chromium – High confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.3. Other RCRA metals – High confidence in ability to pass TCLP/waste acceptance criteria. Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria.

1.2.3. Confidence in total volume of primary and secondary waste forms produced
High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk.

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage.] (See tank leak discussion in Volume I, Section 1.3.3 for more detail.) – Startup in ~5 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~5 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is less impactful because it does not rely on the cross-site transfer line and is more flexible in specific feed piping, tank utilization, etc. As this applies to both 200 West and East Area facilities, it is less directly dependent on specific infrastructure, including DSTs, and would therefore be less impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing the risk of tank leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction near an operating radioactive facility. Some worker exposure to radioactive liquids due to loading/unloading liquid in truck.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (High consequence hazard is not applicable to this alternative since there is no vault.) Over 20 years of operation of saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)] – Moderate risk. High number of radioactive transports. No transports of raw materials onto site; no hazardous liquid chemicals shipped onsite; many radioactive liquid transports of treated supplemental LAW offsite; radioactive liquid transport of evaporator condensate to ETF (assumed to be by truck); many off-site transports of solid radioactive materials (grouted waste) from vendor to off-site disposal facility.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to high discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; evaporator condensate collected to LERF/ETF (~38% of feed volume[2]) containing radioactive and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC-filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Few tanks and process unit operations onsite. Risk of liquid spills during transport of both supplemental LAW to off-site vendor and evaporator condensate to LERF/ETF. Mitigated by experience with shipment of radioactive liquids.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – Low risk of liquid spills during transport of liquid decontaminated supplemental LAW to off-site vendor.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment].] – Minimal solid waste; some equipment and job control waste. Evaporator condensate to LERF (380,000 gallons per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions

[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gallons of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals, assuming that the vendor requires the same amount of electricity and grout formers as was calculated for the Grout 1A alternative (RPP-RPT-63426).

[2] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

There would be additional emissions from transport of liquid to the vendor and then shipping offsite. Expect shipments of ~46,000 grouted waste form boxes to distant disposal location(s) (see Volume II, Section H.9 for more information).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~5 years – Vendors are available with the ability to perform this operation with existing facilities. Time to startup will be a function of the readiness of the Hanford Site to ship material to the vendor and the permitting required to process and dispose of the waste.

2.4.2. Duration to full capacity (additional years) 0 years – Vendors are available with the ability to perform this operation with existing facilities.

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risks of additional mission delays.

2.4.4.1. Delays due to technical/engineering issues – Minimal risk to delay operations; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*),and mitigation is to send noncompatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk of delay. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed of waste). [MOE: Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, but engineering uncertainties are minimal. Uncertainty remains in LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence is reduced waste loading or diverting more waste to LAW melters or vendor treatment.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (by changing grout or GFC recipe, etc.) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading.

3.1.1.1.2. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping.

3.1.1.1.3. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidization methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility but impacts in process delays could occur. Mitigation is potential for off-site vendor treatment.

3.1.1.1.4. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Consequence: Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[3]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment – Metered additions, mechanical mixing, potential offgas generation.

[3] Very low or low complexity/consequences, unless specified otherwise.

- Receipt/storage tank (agitated, cooled?) – Vessel with pumps.
- Receipt tank (agitated, cooled?) – Continuous stirred tank reactor vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container box disassembly and emplacement at off-site location(s) – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition. Moderate consequences.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed overcapacity design of system, lessons learned from SRS or other sites. The use of an off-site grouting facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduces SST leakage risk; reduce cross-site transfer of supernatant liquid.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Only building Tank Farms Pretreatment (TFPT)/LDR evaporator and liquid load-out facility onsite.
- Utility usage (electrical, cooling water, steam, etc. is low).

- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that require diversion.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed.

3.1.1.5. Technology maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990), INL, etc. (including containerized grout). Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for Defense Waste Processing Facility [DWPF] effluents). Alternative assumes that vendor can produce viable waste form. Consequence: Additional development time needed, delayed processing. Moderate consequences.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Very high robustness. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative. Low consequences.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, etc.). Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Unlikely vendors need to expand capacity but expect that vendors could handle variability in flow rates so expansion unlikely to be needed. Some vendors may need permit changes. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending

[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for off-site immobilization will likely be beneath the annual spending benchmark funding level ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for off-site immobilization will likely be beneath the benchmark funding level ($450M/yr).

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] Very high flexibility. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] Scenario is operations more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.)
Operation does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. Sufficient funds would likely be available to perform this alternative by the project need date.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production.] Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only (e.g., off-site vendor; special ingredient; sole source provider).
Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. If the vendor is unable to perform the task, another vendor could be selected.

Off-site disposal location could cease receipt of waste or permission to transport is revoked for unforeseen reasons. Consequence: The process impact would be a delay in processing until an alternative is identified or if an ingredient cannot be procured and one has not been pre-selected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process. A ~2.5-month working inventory of material would remain onsite at the vendor or in-transit until the issue is resolved (maximum of 750 containers).

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. All costs are discounted at 3% rate.

Total: $3,854 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$410 M (includes commissioning costs)

4.2. Operations costs

$3,444 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.13 Selection Criteria Assessment for Alternative Grout 5A

Alternative Grout 5A: Single Supplemental Low-Activity Waste Grout Plant with Monolith in Vault Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in PA.] – High residual toxicity. No reduction in inherent toxicity.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation would be sent to LAW Vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides

[MOE: Estimated peak groundwater concentration at compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (e.g., IDF PA post-compliance period).]

1.1.2.1.1. Iodine – Iodine mobility to groundwater is limited during the first 1,000 years compliance period. Iodine sequestered by long transport pathways provided by vault design. Release would be lower than a containerized waste form without a getter.

Prior performance assessments of vault design showed iodine could exceed peak at extremely long time frames (>10,000 years), but recent modeling suggests improved performance.

1.1.2.1.2. Technetium (confidence in non-pertechnetate is evaluated below) [MOE will be projected concentration in groundwater.] – Technetium mobility to groundwater is limited during the first 1,000 years compliance period. BFS sequesters technetium providing high performance for technetium and long diffusion/transport pathway of vault would slow transport of technetium and slow the reoxidation of the waste form. Prior performance assessments of vault design showed technetium could exceed peak at extremely long time frames (>10,000 years), but recent modeling suggests improved performance.

1.1.2.1.3. Selenium-79 (^{79}Se) – Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3). Assuming high mobility from waste form release to subsurface is many orders of magnitude below conservative DWS and would be even lower for vault design.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives (~30 years) make them only a short-term issue and do not impact PA; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE: Estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Nitrate/nitrite mobility to groundwater is limited during the first 1,000 years compliance period. Retained only by diffusion barrier (physical entrapment), but long pathway would slow release compared to containerized waste form. No comparative performance assessment data of vault design is available for nitrate/nitrite. Need to assume conservative assumptions in subsurface behavior can exceed DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3).

1.1.2.3. Ammonia – No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; no differences between alternatives; ammonia stripped during evaporation immobilized at ETF.]

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Waste form has reduced conditions. Mobility judged against TCLP, which reducing grout consistently passes. Grouted waste form would be expected to be compliant. [1]

1.1.2.4.1. Mercury [MOE is retention of in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS.

[1] See Alternatives Descriptions for metal solidification/stabilization.

1.1.2.4.2. Chromium [MOE is retention of Cr in waste form (grout redox chemistry).] – Cr(VI) sequestered by redox reactions with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty in rate of reoxidation of grout and change in waste form pH; however, long entry pathways will greatly slow these rates compared with a containerized waste form. An oxidized, neutral grout can exceed DWS for chromium. To limit mobility beyond the period of compliance chromium requires maintenance of reducing conditions for a portion of the waste form and maintain alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond period of compliance.

1.1.2.4.3. Other [No MOE needed.] – Projected concentrations of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium. Waste form is expected to pass TCLP for metals.

1.1.3. Total volume of primary and secondary waste forms [MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[2] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*) for containerized grout disposed of in IDF (assume comparable for vault disposal). However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS.

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentrations of LDR organics in the waste. High confidence LDR organics are below limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia concentration will not be significant in grouted tank waste and thus would not present a long-term health risk. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

[2] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.[3]

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.[4]

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity in Hanford environment.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and in the resulting waste form as iodide with a fraction of iodate. Leaching and mobilization of ^{129}I should be reduced or slowed by disposal as a monolith in an engineered vault. Iodine is a key constituent of interest in the IDF PA, and likely also in a PA developed for vault disposal. ^{129}I can define waste classification but concentrations in Hanford tanks likely far lower than Class A limit[5]. Once released by chemical reactions and leached into the subsurface, there is limited to no natural attenuation of iodide, and as such the supplemental LAW iodine inventory could impact groundwater in the post-compliance period. However, a complete assessment of any iodine impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste as predominantly pertechnetate with a fraction of non-pertechnetate. Within the waste form, there is high confidence in the conversion of pertechnetate to a reduced and insoluble technetium form, but behavior of non-pertechnetate is unknown. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form can be destabilized with time due to oxidation, but the rate of reoxidation under the proposed Hanford disposal conditions is unknown; however, the destabilization of ^{99}Tc should be reduced or slowed by disposal as a monolith in an engineered vault. Technetium is a key constituent of interest in the IDF PA and likely also in a PA that would be developed for vault disposal. Technetium can define waste classification, and select tanks have technetium concentrations that approach the Class A limit[6]. Once in the subsurface, there is limited to no natural attenuation of technetium, and as such the supplemental LAW technetium inventory could impact groundwater limits in the post-compliance period.

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[3] See Alternatives Descriptions for metal solidification/stabilization.

[4] See Alternatives Descriptions for metal solidification/stabilization.

[5] ^{129}I is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

[6] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

However, complete assessment of any technetium impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.3. ^{79}Se – Limited to no data available on speciation in the waste, in grout, or mobility within grout waste forms. Expect to remain as a soluble species in grout interstitial voids, retained by diffusion barrier; however, disposal as a monolith in an engineered vault would significantly reduce interaction with the environment (see SRS Saltstone Disposal Unit [SDU] performance). Limited attenuation in the Hanford subsurface. High confidence of minimal impact due to minimal inventory (144 Ci or ~2 kg, per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*). Furthermore, disposal as a monolith in an engineered vault would significantly reduce interaction with the environment (see SRS SDU PA).

1.2.2.4. Nitrates/nitrites – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are mobile in grout waste forms and will not be slowed without formulation modification; however, disposal as a monolith in an engineered vault would significantly reduce infiltration of water and interaction with and release to the environment (see SRS SDU performance). Nitrate and nitrite are a key constituent but would not drive waste classification or waste acceptance criteria. There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford tanks, and a recent assessment projected concentrations slightly above compliance limits using a projection of a non-optimized grout waste form disposed of in IDF, but likely diminished when disposed of in a vault. As such there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.5. Ammonia/ammonium ion – Very high confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration, especially when disposed of as a monolith in an engineered vault. Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal impact.

1.2.2.6. RCRA metals[7]

1.2.2.6.1. Mercury – Very high confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation, but low confidence in mercury speciation in tank waste; however, this lack of confidence obviated by disposal as a monolith in an engineered vault. Upon release (and after leachate system no longer effective), high confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface.

[7] See Alternatives Descriptions for metal solidification/stabilization.

1.2.2.6.2. Chromium – Very high confidence in sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment (however, this uncertainty obviated by disposal as a monolith in an engineered vault that limits interaction with the environment). High confidence in knowledge of subsurface mobility (after leachate system no longer effective); there is limited attenuation in the subsurface although some mineral interactions (iron, carbonate, barium) have been observed.

1.2.2.6.3. Other RCRA metals – Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste forms serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria.

Disposal as a monolith in an engineered vault further limits water infiltration and interaction with and release to the environment. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP for the RCRA metals.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – Very high confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration.)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration.] Moderate risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.3 for more detail.)] – Startup in ~13 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~13 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks.

Continuity of operations after startup – loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire benchmark initial supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction is likely near an operating radioactive facility (LAW Vitrification Facility); this construction would be shorter duration in comparison to other alternatives.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components for grout plant. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards and one high consequence hazard (RPP-RPT-63426). Over 30 years of operation of Saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste poured into a vault.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to highest number of shipments.)]
Low risk. Large number of transports of raw materials onto site; no hazardous liquids shipped onsite; no rad liquid transport; no off-site transport of radioactive materials.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; all LAW/flush water is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[8]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Minimal risk, few tanks and process unit operations. Only risk is transfers to evaporator and LERF/ETF, liquid to grout plant, and grout slurry to vault.

[8] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.3.4. Off-site transportation spills
[MOE: No risk of off-site spills to high risk for off-site spills.] – Negligible risk. Only possible is material transport truck/railcar accident of non-rad minimally hazardous dry solid ingredients.

2.3.5. Secondary waste streams generated
[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment].] – Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions
[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426).

2.4. Duration

2.4.1. Duration to hot startup (years) ~13 years.

2.4.2. Duration to full capacity (additional years) 1 year.

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delay

2.4.4.1. Delays due to technical/engineering issues – Minimal risk to delay operations due to grout technology; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*). (Delays due to technical uncertainties contribute to increased cost risk and therefore potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste.) [MOE: Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, but engineering uncertainties are minimal.

Some uncertainty in ability to remove LDR organics remains, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence is potential delays in processing. Low likelihood of failure.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading. Low consequences.

3.1.1.1.2. Suitable getter (iodine and potentially technetium) not identified/long-term performance inadequate – This alternative does not require getters. For disposal as a monolith in an engineered vault, iodine getters are not necessary for acceptable performance of the grouted waste form. Thus, the consequence of not identifying a suitable getter would be lack of potential defense in depth; however, the waste form disposed of as a monolith in a vault would still be acceptable. Low consequences.

3.1.1.1.3. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping. Mitigated by years of operation of nearly identical process at SRS with disposal in large vaults.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed enough to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility, but impacts in process delays could occur.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[9]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – CSTR vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/vault filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Remote vault fill station – Provides distribution of flow to allow lifts and flushing/cold cap deployment.
- Vault construction – Construction of large vaults is demonstrated but challenging.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slowly or not at all, or does not flow into vault, requiring modification of composition (moderate consequences).

[9] Very low or low complexity/consequences, unless specified otherwise.

- Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Expect that design would be nearly identical to SRS SDU. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – mostly commercially available equipment, experience with SDU vaults.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple - feed line to facility all that is needed except for feeds with LDR organics that would require diversion.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier.

3.1.1.5. Technology maturity, including Test Bed Initiative [MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general has been demonstrated at full scale; Saltstone at SRS (similar process, scale, monolithic engineered vault, and waste operations since 1990) and other sites. Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents) Consequence: Additional development time needed, delayed processing. Moderate consequences.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also) [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood but could be further optimized. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities. Recovery from extended process interruptions demonstrated at SRS. Engineered vault considered more robust than containers in IDF.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Moderate robustness. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered costly and time consuming to retrieve a grout monolith from a vault with current techniques than a containerized form. Consequence: Section the material for excavation or add an additional robust cap (for example) or barrier or other technology may be an alternative because the waste is in isolated vaults. Moderate consequences.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it can be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: easily incorporate to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for a supplemental LAW grout facility and engineered vaults will likely be significantly beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending
[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for a supplemental LAW grout facility and engineered vaults will likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget
[MOE: Ability to start and stop construction and operations in response to external factors.] – Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. Very low likelihood of failure. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Operations more expensive than expected for grout disposed of in a vault; or vault construction. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution and sunk cost for the facility and first SDU. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to complete a grout facility by the project need date because of low cost.

***3.3. Likelihood and consequences of failing to complete due to* unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute, if the need arises. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been pre-selected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $3,349 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,735 M (includes commissioning costs)

4.2. Operations costs

$1,614 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.14 Selection Criteria Assessment for Alternative Grout 5B

Alternative Grout 5B: Single Supplemental Low-Activity Waste Grout Plant with Containers in Vault Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents to all retained to amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in PA.] – High residual toxicity. No reduction in inherent toxicity.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation would be sent to LAW Vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions [No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides – [MOE: Estimated peak groundwater concentration at compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (e.g., IDF PA post-compliance period).]

1.1.2.1.1. Iodine – Iodine mobility to groundwater is limited during the first 1,000 year compliance period. Iodine sequestered by long transport pathways provided by vault design. Release would be lower than a containerized waste form without a getter. Prior performance assessments of vault design showed iodine could exceed peak at extremely long time frames (>10,000 years), but recent modeling suggests improved performance.

1.1.2.1.2. Technetium (confidence in non-pertechnetate is evaluated below) [MOE will be projected concentration in groundwater.] – Technetium mobility to ground water is limited during the first 1,000 year compliance period. BFS sequesters technetium providing high performance for technetium and long diffusion/transport pathway of vault would slow transport of technetium and slow the reoxidation of the waste form. Prior performance assessments of vault design showed technetium could exceed peak at extremely long time frames (>10,000 years), but recent modeling suggests improved performance.

1.1.2.1.3. Selenium-79 (^{79}Se) – Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3). Assuming high mobility from waste form release to subsurface is many orders of magnitude below conservative DWS and would be even lower for vault design.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives (~30 years) make them only a short-term issue and do not impact PA; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Nitrate/nitrite mobility to ground water is limited during the first 1,000 year compliance period. Retained only by diffusion barrier (physical entrapment) but long pathway would slow release compared to containerized waste form. No comparative performance assessment data of vault design is available for nitrate/nitrite. Need to assume conservative assumptions in subsurface behavior can exceed DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3).

1.1.2.3. Ammonia – No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; no differences between alternatives; ammonia stripped during evaporation immobilized at ETF.]

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Waste form has reduced conditions. Mobility judged against TCLP, which reducing grout consistently passes. Grouted waste form would be expected to be compliant.[1] Disposal in containers in an engineered vault would add defense in depth.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form (grout redox chemistry).] – Cr(VI) sequestered by redox reactions with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty in rate of reoxidation of grout and change in waste form pH; however, long entry pathways will greatly slow these rates compared with a containerized waste form. An oxidized neutral grout can exceed DWS for chromium.

[1] See Alternatives Descriptions for RCRA metal solidification/stabilization

To limit mobility beyond the period of compliance chromium requires maintenance of reducing conditions for a portion of the waste form and maintain alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond period of compliance.

1.1.2.4.3. Other [No MOE needed.] – Projected concentrations of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium. Waste form is expected to pass TCLP for metals.

1.1.3. Total volume of primary and secondary waste forms [MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[2] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume would be minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*) for containerized grout disposed of in IDF (which would be the same for the containers for vault disposal). However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS.

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity (MOE: High confidence in value to low confidence.)

1.2.1.1. LDR organics – Moderate uncertainty with the concentrations of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia concentration would not be significant in grouted tank waste and thus would not present a long-term health risk. Tank waste contains only small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.[3]

[2] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

[3] See Alternatives Descriptions for RCRA metal solidification/stabilization information.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity in Hanford environment.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and in the resulting waste form as iodide with a fraction of iodate. Leaching and mobilization of ^{129}I should be reduced or slowed by disposal in containers in an engineered vault (where any intact polypropylene liners would add defense in depth). Iodine is a key constituent of interest in the IDF PA, and likely also in a PA developed for vault disposal. ^{129}I can define waste classification but concentrations in Hanford tanks likely far lower than Class A limit[4]. Once released by chemical reactions and leached into the subsurface there is limited to no natural attenuation of iodide, and as such the supplemental LAW iodine inventory could impact groundwater in the post-compliance period. However, a complete assessment of any iodine impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste as predominantly pertechnetate with a small fraction of non-pertechnetate in most tanks. Within the waste form, there is high confidence in the conversion of pertechnetate to a reduced and insoluble technetium form, but behavior of non-pertechnetate is unknown. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form can be destabilized with time due to oxidation, but the rate of reoxidation under proposed Hanford disposal conditions is unknown; however, the destabilization of ^{99}Tc should be reduced or slowed by disposal in containers in an engineered vault (where any intact polypropylene liners would add defense in depth). Technetium is a key constituent of interest in the IDF PA and likely also in a PA that would be developed for vault disposal. Technetium can define waste classification and select tanks have technetium concentrations that approach the Class A limit[5]. Once in the subsurface there is limited to no natural attenuation of technetium, and as such the supplemental LAW technetium inventory could impact groundwater limits in the post-compliance period. However, complete assessment of any technetium impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

[4] ^{129}I is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

[5] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

1.2.2.3. ^{79}Se – Limited to no data available on speciation in the waste, in grout, or mobility within grout waste forms. Expect to remain as a soluble species in grout interstitial voids, retained by diffusion barrier; however, disposal in containers in an engineered vault (where any intact polypropylene liners would add defense in depth) would significantly reduce interaction with the environment (see SRS SDU PA). Limited attenuation in the Hanford subsurface. High confidence of minimal impact due to minimal inventory (144 Ci or ~2 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*). Furthermore, disposal in containers in an engineered vault would significantly reduce interaction with the environment (see SRS SDU PA).

1.2.2.4. Nitrates/nitrites – High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are mobile in grout waste forms and would not be slowed without formulation modification; however, disposal in containers in an engineered vault (where any intact polypropylene liners would add defense in depth) would significantly reduce infiltration of water and interaction with and release to the environment (see SRS SDU PA). Nitrate and nitrite are a key constituent, but would not drive waste classification or waste acceptance criteria. There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford tanks, and a recent assessment projected concentrations slightly above compliance limits in the post-compliance period using a projection of a non-optimized grout waste form disposed of in IDF, but likely diminished when disposed of in an engineered vault. As such, there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior).

1.2.2.5. Ammonia/ammonium ion – Very high confidence that grouted tank waste would not be a source of significant leaching of ammonium ion due to low concentration, especially when disposed of in containers in an engineered vault (where any intact polypropylene liners would add defense in depth). Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal additional impact.

1.2.2.6. RCRA metals[6]

1.2.2.6.1. Mercury – Very high confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation, but low confidence in mercury speciation in tank waste; however, this is obviated by disposal in containers in an engineered vault (where any intact polypropylene liners would add defense in depth). Upon release (and after leachate system no longer effective), high confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface.

[6] See Alternatives description for sequestration of metals

1.2.2.6.2. Chromium – Very high confidence in sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment (however, this is obviated by disposal in containers in an engineered vault [where any intact polypropylene liners would add defense in depth] that limits interaction with the environment). High confidence in knowledge of subsurface mobility (after leachate system no longer effective); there is limited attenuation in the subsurface although some mineral interactions (iron, carbonate, barium) have been observed.

1.2.2.6.3. Other RCRA metals – Moderate confidence on speciation in waste and resulting waste form due to limited data. High confidence that the use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria.

Disposal in containers in an engineered vault (where any intact polypropylene liners would add defense in depth) further limits water infiltration and interaction with and subsequent release to the environment. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP for the RCRA metals[7].

1.2.3. Confidence in total volume of primary and secondary waste forms produced – Very high confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration.)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk

[MOE is time to start and processing duration.] Moderate risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.3 for more detail.)] – Startup in ~13 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~13 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks.

Continuity of operations after startup – loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

[7] See Alternatives description for sequestration of metals

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing risk of leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction is likely near an operating radioactive facility (LAW Vitrification Facility); this construction would be shorter duration in comparison to other alternatives.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components for grout plant. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards and one high consequence hazard (RPP-RPT-63426). Over 30 years of operation of Saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste disposed of in a vault; albeit poured as grout slurry instead of containers.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to highest number of shipments.)] – Low risk. Large number of transports of raw materials onto site and waste form boxes onsite; no hazardous liquids shipped onsite; no rad liquid transport; no off-site transport of radioactive materials.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal risk; all LAW/flush water is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[8]) containing rad and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

[8] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.3.2. Atmospheric discharges
[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)
[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Minimal risk, few tanks, and process unit operations. Only risk is transfers to evaporator and LERF/ETF.

2.3.4. Off-site transportation spills
[MOE: No risk of off-site spills to high risk for off-site spills.] – Very low risk. Only possible is material transport truck/railcar accident of non-rad minimally hazardous dry solid ingredients.

2.3.5. Secondary waste streams generated
[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment].] – Very low volume. Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions
[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426). (See Volume II, Section H.9 for more information.)

2.4. Duration

2.4.1. Duration to hot startup (years) ~13 years.

2.4.2. Duration to full capacity (additional years) 1 year.

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delay

2.4.4.1. Delays due to technical/engineering issues – Minimal risk to delay operations due to grout technology; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR organic removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*). (Delays due to technical uncertainties contribute to increased cost risk and therefore potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste.) [MOE: Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The grout alternative will use the same flowsheet and approach as the existing SRS facility.

Formulations will vary somewhat, but engineering uncertainties are minimal. The baseline process is considered robust to be able to immobilize the waste into a grout waste form. Low likelihood of failure.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading. Low consequences.

3.1.1.1.2. Suitable getter (iodine and potentially technetium) not identified/long term performance inadequate – This alternative does not require getters. Medium likelihood and low consequence. For disposal in containers in an engineered vault, iodine getters are not necessary for acceptable performance of the grouted waste form. Thus, the consequence of not identifying a suitable getter would be lack of potential defense in depth; however, the waste form disposed in containers in an engineered vault would still be acceptable.

3.1.1.1.3. Transport lines become blocked/congested or leak – Very low likelihood. Grout is a simple process with a small number of lines. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is very low; replacement of piping. Mitigated by years of operation of nearly identical process at SRS with disposal in large vaults.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed enough to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods.

Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility, but impacts in process delays could occur.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Very low; delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[9]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – CSTR vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch Mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container box disassembly and emplacement in vault – Forklift and crane operations.

[9] Very low or low complexity/consequences, unless specified otherwise.

- Vault construction – Construction of large vaults demonstrated at SRS.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slowly or not at all, or does not flow into vault, requiring modification of composition (moderate consequences).
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Expect that design would be nearly identical to SRS SDU. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with SDU vaults at SRS.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that would require diversion.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general has been demonstrated at full scale; Saltstone at SRS (similar process, scale, monolithic engineered vault, and waste operating since 1990) and other sites. Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Evaporation of alkaline tank waste has been done for decades at Hanford and SRS, but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Consequence: Additional development time needed, delayed processing; moderate consequences.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also) [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood but could be improved. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities. Recovery from extended process interruptions demonstrated at SRS. Engineered vault considered more robust than containers in IDF.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Very high robustness. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the containerized waste form from the engineered vault with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative. Low consequences.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it can be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component) as demonstrated as SRS and elsewhere. Systems and unit operations are relatively inexpensive. Updates to grout formulation easily incorporated.

Ability to expand capacity would be challenging but expect that initial system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for a supplemental LAW grout facility and engineered vaults would likely be significantly beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for a supplemental LAW grout facility and engineered vaults would likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. Very low likelihood of failure. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Operations more expensive than expected for containerized grout; or vault construction. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution and sunk cost for the facility and first engineered vault. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is likely that sufficient funds will be available to complete a grout facility by the project need date because of low cost.

***3.3. Likelihood and consequences of failing to complete due to una*vailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute, if the need arises. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been pre-selected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate; costs are the same as Grout 5A, within estimate range.)

Total: $3,349 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,735 M (includes commissioning costs)
includes six grout disposal units (includes $90 M commissioning costs)

4.2. Operations costs

$1,614 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

D.2.15 Selection Criteria Assessment for Alternative Grout 6

Alternative Grout 6: Phased Off-site and On-site Grouting in Containers

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents - all retained – to amount increased by treatment.] – Applicable to all three phases.

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; All alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for the long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides [MOE: Estimated peak groundwater concentration at compliance point over ~1,000 years (e.g., DOE O 435.1; IDF PA compliance point and period); identify peak to 10,000 years to address longer-term groundwater protection (e.g., post-compliance period).]

1.1.2.1.1. Iodine – Onsite: Iodine mobility to ground water is limited during the first 1,000 years compliance period. Iodine sequestered by getter leads to enhanced retention in waste form; relative to non-getter waste form. Projected ~100× below DWS (maximum contaminant level) per NDAA17 report but uncertainty in long-term performance with only laboratory data to date. Iodine not bound to getter could exceed DWS.

To limit mobility beyond the period of compliance, iodine requires stability of getter phase to meet concentration limits.

On-site inventory from supplemental LAW reduced by ~50% or more. Inventory remaining onsite is assumed to scale proportionally to peak dose at point of compliance. Offsite: No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.1.2.1.2. Technetium – Onsite: Technetium mobility to ground water is limited during the first 1,000 years (compliance period) due to facility performance. BFS sequesters technetium providing high performance for technetium; ~10× below DWS per NDAA17 report; uncertainty in rate of reoxidation of grout in IDF; an oxidized grout could exceed DWS. To limit mobility beyond the period of compliance, technetium requires maintaining reducing conditions for a portion of the waste form during disposal to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout. On-site inventory from supplemental LAW reduced by ~50% or more. Inventory remaining onsite will scale proportionally to peak dose at point of compliance. (Non-pertechnetate will be evaluated below in confidence.) Offsite: No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3.1.3). On-site inventory reduced by this alternative. Offsite: No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Onsite: Nitrate/nitrite mobility to groundwater is limited during the first 1,000 years compliance period. Retained only by diffusion barrier (physical entrapment). Recent diffusivity testing shows some formulations can retain nitrate/nitrate more effectively and estimate peak concentrations below the compliance standard. These tests were performed in a conservative, saturated environment, which would produce much greater release rates than actual unsaturated conditions in the IDF.

Conservative assumptions regarding nitrate/nitrate subsurface behavior could result in exceedance of DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3). On-site inventory reduced by this alternative in roughly the same fraction as the disposed volume.

Offsite: No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting the site's license requirements.

1.1.2.3. Ammonia – Onsite: No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; ammonia stripped during evaporation is immobilized at ETF.] Ammonia from this option is low in the grouted secondary waste disposed of in IDF but ammonia will still be present from LAW melter system so is not differentiating among alternatives. Offsite: Minimal impact to Hanford groundwater due to grouted ETF solids. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting the site's license requirements.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Mobility judged against TCLP, which reducing grout consistently passes. Onsite: Waste form has reduced toxicity. Grout waste form would be compliant. Offsite: Grout waste form would pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory. Onsite: Sequestered by sulfide reaction with BFS. Offsite: Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form (grout redox chemistry).] – Onsite: Cr(VI) sequestered by redox reactions with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty exists in rate of reoxidation of grout in IDF and change in waste form pH; an oxidized, neutral grout could exceed DWS for chromium. To limit mobility beyond the period of compliance, chromium requires maintaining reducing conditions for a portion of the waste form and maintaining alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond the period of compliance. Offsite: Grout waste form would pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.3. Other [No MOE needed.] – Onsite: Projected concentrations of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium. Offsite: Grout waste form would pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include the evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS. Onsite: Total volume remaining onsite reduced by 30% or more.

1.2. Long-term risks upon successful completion
[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or could be removed/destroyed to beneath regulatory limits, if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and in the resulting waste form as iodide with a fraction of iodate. Moderate confidence in the immobilization of AgI from reaction with getter in the waste form, but any unreacted free iodide/iodate would be mobile. Success of the silver precipitation approach has been shown at the laboratory-scale using getters but not demonstrated at pilot- or process-scale.

[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

The immobile fractions as AgI can destabilize with time due to chemical reduction of Ag^{+} to Ag^{0} and competition with other species (e.g., sulfide that can form Ag_2S), the rate of these destabilization processes in the disposed waste form is untested. Iodine is a key constituent of interest in the IDF PA.

^{129}I can define waste classification but concentrations in Hanford tanks are likely far lower than Class A limit.[2] Once released by chemical reactions and leached into the subsurface, there is limited to no natural attenuation of iodide, and as such the supplemental LAW iodine inventory could impact groundwater limits in the post-compliance period. However, a complete assessment of iodine impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior) and important uncertainties. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.2. Technetium (including non-pertechnetates) – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste as pertechnetate with a fraction of non-pertechnetate. Within the waste form, there is high confidence in the conversion of pertechnetate to a reduced and insoluble technetium, but there is an unknown behavior of non-pertechnetate. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form could be destabilized with time due to oxidation but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA. Technetium can define waste classification and select tanks have technetium concentrations that approach the Class A limit.[3] However, a complete assessment of technetium impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior) and important uncertainties. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.3. ^{79}Se – Limited to no data available on the speciation in the waste, in grout, or mobility within grout waste forms. Limited attenuation in the Hanford subsurface. High confidence of minimal impact due to minimal inventory (144 Ci or ~2 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*). Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

[2] ^{129}I is listed in Table 1 of 10 CFR 61.55, Waste Classification, that is used to classify wastes for near-surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

[3] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 that is used to classify wastes for near-surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

1.2.2.4. Nitrates/nitrites – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are not retained in grout waste forms and will not be slowed without formulation modification. Nitrate and nitrite are a key constituent within the IDF but will not drive waste classification or waste acceptance criteria.

There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford tanks, and a recent assessment projected concentrations slightly above groundwater limits in the post-compliance period using a projection of a non-optimized grout waste form disposed of in IDF (under saturated, non-conservative conditions resulting in higher than expected release).

As such, there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior) and important uncertainties. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.5. Ammonia/ammonium ion – Onsite: High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal impact. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – High confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation, but low confidence in mercury speciation in tank waste. High confidence in limited subsurface transport and limited knowledge on speciation changes in subsurface.

1.2.2.6.2. Chromium – High confidence in ability to pass TCLP due to sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment and high confidence in knowledge of subsurface mobility; there is limited attenuation in the IDF backfill and subsurface although some mineral interactions (e.g., iron, carbonate, barium) have been observed. Chromate is slow moving in subsurface and expected to be compliant with DWS.

1.2.2.6.3. Other RCRA metals –. High confidence in ability to pass TCLP. Moderate confidence of speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP; however, if Ag is added as iodine getter, this adds uncertainty.

1.2.3. Confidence in total volume of primary and secondary waste forms produced
High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk.
[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage.] (See tank leak discussion in Volume I, Section 1.3.3 for more detail.) – Startup in ~5 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~5 years has lower risk of additional tank leaks because retrievals would be earlier than currently scheduled and would support HLW, allowing the lowest time for additional corrosion-induced tank leaks. This alternative would keep HLW processing on schedule.

Continuity of operations after startup – depending on when an unforeseen event (e.g., tank leak) happens, loss of specific DSTs is more or less impactful. During the initial phase when liquid is shipped offsite, continuity is less dependent on infrastructure items, like the cross-site transfer line. But in later phases when operations transition to on-site production of grout, continuity is dependent on the cross-site transfer line, specific feed piping, tank utilization, etc. Since this has both 200 East and West Area facilities, continuity of operations is directly dependent on specific infrastructure, including DSTs, and would therefore be partially impacted by failure of key staging and transfer tanks.

This alternative is intended to consume the entire initial benchmark supplemental LAW treatment budget and takes advantage of the opportunity for an early start as part of a hybrid or concurrent alternative treatment. There is potential for reducing risk of tank leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety
[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporization of radionuclides. Some construction is near an operating radioactive facility (LAW Vitrification Facility); construction would have shorter duration intervals in comparison to other alternatives.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabrication hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (One high consequence hazard is not applicable to this alternative since there is no monolith in a vault). Over 20 years of operation of saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)]
Large number of transports of raw materials onto site and waste form boxes onsite; large number of radioactive and hazardous liquid transports. Onsite: Large number of solid radioactive waste form packages. Offsite: Many off-site transports of liquid and/or solid radioactive waste form packages to distant location(s). Practical impact would be negligible because transport of low dose solid and liquid radioactive materials is well known.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; all LAW/flush water during grouting is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[4]) containing radioactive and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases likely; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Risk of liquid spills during transport of both LAW to off-site vendor and evaporator condensate to LERF/ETF. Mitigated by experience with shipment of radioactive liquids.

[4] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.3.4. Off-site transportation spills
[MOE: No risk of off-site spills to is high risk for off-site spills.] – Moderate risk of liquid spills during transport of liquid decontaminated LAW for off-site disposal. Large numbers of radioactive shipments, both liquid and (potentially) solids. Mitigated by experience with off-site shipment of radioactive liquids.

2.3.5. Secondary waste streams generated
[MOE: Volume of waste (liquid, solids, and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment] – Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions
[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426). Offsite: Expect shipments of ~15,000 or more grouted waste form boxes to distant disposal location(s) (see Volume II, Section H.9 for more information).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~5 years.

2.4.2. Duration to full capacity (additional years) 1 year.

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delays

2.4.4.1. Delay due to technical/engineering issues – Minimal risk to delay operations; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*)and mitigation is to send non-compatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities is expected to shorten the duration of supplemental LAW (and HLW) processing.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: tech failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences] Low risk. The grout alternative would use the same flowsheet and approach as the existing SRS facility. Formulations would vary somewhat, and getters would be included, but engineering uncertainties are minimal.

Uncertainty remains in the utility of getters at scale and LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence of failure to identify a suitable iodine getter or remedy results in failure in ability to dispose of waste onsite in IDF and shipping more waste offsite or to the LAW melters.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process would be able to produce an acceptable grout from the entire waste feed vector and to restart quickly from a cold shutdown, which provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives and reduced waste loading.

3.1.1.1.2. Suitable getter (iodine and potentially technetium) not identified/long-term performance inadequate – Medium likelihood and high consequence for on-site disposal of grouted waste. While suitable getters for technetium and iodine have been tested in the laboratory, the application of these getters in a production process and in conjunction with each other has not been demonstrated. Consequence of not identifying suitable getters would be that on-site disposal of the grout is not permitted and other methods to sequester iodine (and potentially technetium) are not identified. Off-site disposal – getter/waste form performance not needed; very low risk.

3.1.1.1.3. Transport lines become blocked/congested or leak – Very low likelihood – Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits, if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility but impacts in process delays could occur. Mitigation is potential for off-site vendor treatment.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk – The LDR organics are assumed to identified during batch qualification and detection limits can be reached for organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Grouting of the supplemental LAW feed requires few integrated unit operations.
The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections are needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – Vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment/load out station – Hoist and forklift operations.
- Container box disassembly and emplacement at IDF – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-spec composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites. The use of an off-site grout production facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduce SST leakage risk; and reduce cross-site transfer of supernatant liquid.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on collocated processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line is not needed to support this alternative.
- Rail line spur.
- Liquid loadout facility.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier. Offsite: Off-site disposal locations may need expansion.

3.1.1.5. Technology Maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Shipping grouted Hanford waste offsite successfully demonstrated during Test Bed Initiative. Grout in general has been demonstrated at scale; saltstone at SRS (similar process, scale, and waste operations since 1990) and INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Adding iodine getters has not been demonstrated at scale. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Consequence: Continue shipping offsite until onsite is available.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, remediating the waste form could be necessary. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (e.g., as a defense-in-depth measure) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Unlikely vendors need to expand capacity but expect that vendors could handle variability in flow rates so expansion unlikely to be needed. Some vendors may need permit changes. Consequence: Minimal cost and short delays. Expect that initial on-site system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays. Additional time to begin on-site disposal allows additional development time.

3.2. Likelihood and consequences of failing to complete due to resource constraints
[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – The funding needs for a supplemental LAW grout facility would likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr). Spending includes both 200 East Area plant construction while also paying off-site vendor and transporting waste, but benefit is early start.

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget] – The peak funding needs for a supplemental LAW grout facility would likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr). Higher costs overall but could spread costs over one additional year.

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. Grout facilities are typically able to operate below maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.)
Operations, shipping, and disposal are more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and require need to select alternate solution. Off-site disposal option allows flexibility in the event of on-site disposal issues and off-site immobilization step mitigates on-site facility issues. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the on-site facilities does not start or stops until funding is available. Worst case is to continue off-site grout. Consequence: Costs of off-site disposal and grouting must continue longer than projected. Sufficient funds would likely be available to complete a grout capability by the project need date.

3.3. ***Likelihood and consequences of failing to complete due to*** **unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).]
Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. If the vendor is unable to perform the task, another vendor could be selected. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been preselected. Offsite: Another disposal location must be identified.

Limited use of sampling because the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. All costs are discounted at 3% rate.

Total: $4,127 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,393 M (includes for commissioning costs)

4.2. Operations costs

$2,734 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

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Appendix E. Uncertainties

E.1 INTRODUCTION

Crucial to the alternatives analysis was consideration of uncertainties in the assessments for each criterion. Specific criteria carried more weight than others, and as such uncertainty around these criteria would drive overall uncertainty in the achievability and success of each alternative. This appendix will first present a summary of the main uncertainty drivers and technical risks in each section of the analysis criteria (Section E.2). This summary is then followed by expanded descriptions of the uncertainty/risk items listed: Section E.3 (grout), Section E.4 (costs), Section E.5 (vitrification), and Section E.6 (FBSR). The uncertainties/risks presented focus solely on the drivers that lead to the final assessment ranking. For details on the other uncertainties considered, but that did not impact the overall assessment, a brief description is given in Section E.7.

E.2 UNCERTAINTY DRIVERS IN ALTERNATIVES

In the evaluation of the various alternatives (Volume II, Appendix D), the final rankings contained a summary of uncertainty and technical risks around the assessments of the four main criteria: long-term effectiveness (environmental and safety risk after disposal) (C1), implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration) (C2), likelihood of successful mission completion (including affordability and robustness to technical risks) (C3), and lifecycle costs (discounted) (C4). There could be low uncertainty (high certainty) around an assessment that was strong or poor, and vice versa. For example, a criteria with a rating of "Low probability with low uncertainty" is one where there is high confidence that even with a breakthrough the alternative will still have low probability of success. The sources of uncertainty/risk in each criteria vary between the alternatives. Table E-1 (on the next page) lists the uncertainty/risk classification for the three main criteria (C1–C3) for each alternative and where a "moderate" or "high" ranking of uncertainty/risk was given, the driver(s) of that uncertainty is listed. More detailed descriptions of these drivers are given in the subsequent section or callouts to supporting text in the report. A brief description of the uncertainty in the lifecycle costs (discounted) (C4) is also given. The criteria for uncertainty and risk for the three levels is defined as follows:

- **Low uncertainty/risk** – Sufficient supporting data/experience exists for all sub-criteria. The overall assessments made are unlikely to change with future developments/changes. High confidence could be assigned to the descriptions provided of each criteria.
- **Moderate uncertainty/risk** – Sufficient supporting data/experience exists for most sub-criteria. For select criteria, gaining further knowledge/development could have an impact on the overall assessments made. Technical challenges identified are considered feasible to overcome with future development. High confidence could be assigned to the descriptions provided of most criteria and discrete uncertainties were identified.
- **High uncertainty/risk** – Minimal supporting data/experience exists for select sub-criteria that are considered crucial for success of the alternative. For select criteria gaining further knowledge/ development could have an impact on the overall assessments made. Technical challenges identified are considered unlikely to overcome without significant breakthroughs. Low confidence could be assigned to the descriptions provided of most criteria, and several broad uncertainties were identified.

Table E-1. Summary of Primary Uncertainty Drivers in Each Alternative

Alternative[a]	C1 Uncertainty Associated with Effectiveness Ranking	C2 Risk Associated with Mission Duration and Technical Risks	C3 Uncertainty Associated with Probability Ranking
Vitrification 1	***Moderately Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Secondary waste inventory, volume and disposal location of secondary waste • Fate of CoCs (radionuclides and hazardous contaminants) in secondary wastes	***DNF even if executed as intended with Moderate Technical Risk of Operations*** *Technical Risk of Operations* • Delays due to annual operating costs exceeding budget • Radiation exposure • Chemical exposure • Intentional wastewater discharges • Secondary waste streams generated	***Extremely Low Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
FBSR 1A	***Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Mobility of iodine, technetium, and nitrate to PW and associated confidence in immobilization • Tc, I and Hg partitioning • Effectiveness of nitrate/nitrate destruction • Amount of and performance of Tc/I in waste form	***DNF even if executed as intended with High Technical Risk of Operations*** *Technical Risk of Operations* • Delays due to technical issues • Delays due to annual operating costs exceeding budget • Radiation exposure • Chemical exposure • Particulate Exposure	***Extremely Low Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
FBSR 1B	***Highly Effective with Respect to Long-term Immobilization with High Confidence in that Assessment*** *Uncertainty Drivers: None*	***DNF even if executed as intended with High Technical Risk of Operations*** *Technical Risk of Operations* • Delays due to technical issues • Delays due to annual operating costs exceeding budget • Radiation exposure • Chemical exposure • Particulate Exposure	***Low Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 1A	***Moderately Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Mobility of iodine, technetium, and nitrate to PW and associated confidence in immobilization • Effectiveness of treatment for LDR organics, if needed	***40-45 Years if Executed as Intended with Low Technical Risk of Operations***	***Very High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 1B	***Highly Effective with Respect to Long-term Immobilization with High Confidence in that Assessment*** *Uncertainty Drivers: None*	***40-45 Years if Executed as Intended with Low Technical Risk of Operations***	***Very High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*

Table E-1. Summary of Primary Uncertainty Drivers in Each Alternative

Alternative[a]	C1 Uncertainty Associated with Effectiveness Ranking	C2 Risk Associated with Mission Duration and Technical Risks	C3 Uncertainty Associated with Probability Ranking
Grout 1C	***Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Mobility of technetium (non-pertechnetate) and nitrate to PW and associated confidence in immobilization • Effectiveness of treatment for LDR organics, if needed • Efficiency/maturity of iodine removal materials	***40-45 Years if Executed as Intended with Low Technical Risk of Operations***	***High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 1D	***Effective with Respect to Long-term Immobilization with High Confidence in that Assessment*** *Uncertainty Drivers: None*	***40-45 Years if Executed as Intended with Low Technical Risk of Operations***	***Very High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 2A	***Moderately Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Mobility of iodine, technetium, and nitrate to PW and associated confidence in immobilization • Effectiveness of treatment for LDR organics, if needed	***40-45 Years if Executed as Intended with Low Technical Risk of Operations***	***High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 2B	***Highly Effective with Respect to Long-term Immobilization with High Confidence in that Assessment*** *Uncertainty Drivers: None*	***40-45 Years if Executed as Intended with Low Technical Risk of Operations***	***High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 2C	***Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Mobility of technetium (non-pertechnetate) and nitrate to PW and associated confidence in immobilization • Effectiveness of treatment for LDR organics, if needed • Efficiency/maturity of iodine removal materials	***40-45 Years if Executed as Intended with Low Technical Risk of Operations***	***High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 4A	***Moderately Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Mobility of iodine, technetium, and nitrate to PW and associated confidence in immobilization • Effectiveness of treatment for LDR organics, if needed	***40-45 Years if Executed as Intended with Moderate Technical Risk of Operations*** – *Technical Risks:* • Increased transportation requirements	***Very High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*

Table E-1. Summary of Primary Uncertainty Drivers in Each Alternative

Alternative[a]	C1 Uncertainty Associated with Effectiveness Ranking	C2 Risk Associated with Mission Duration and Technical Risks	C3 Uncertainty Associated with Probability Ranking
Grout 4B	***Highly Effective with Respect to Long-term Immobilization with High Confidence in that Assessment*** *Uncertainty Drivers: None*	***40-45 Years if Executed as Intended with Moderate Technical Risk of Operations*** – *Technical Risks:* • Increased transportation requirements	***Very High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 5A	***Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Mobility of iodine, technetium, and nitrate to PW and associated confidence in immobilization in vault • Effectiveness of treatment for LDR organics, if needed	***40-45 Years if Executed as Intended with Low Technical Risk of Operations***	***High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 5B	***Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Mobility of iodine, technetium, and nitrate to PW and associated confidence in immobilization in vault • Effectiveness of treatment for LDR organics, if needed	***40-45 Years if Executed as Intended with Low Technical Risk of Operations***	***High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*
Grout 6	***Highly Effective with Respect to Long-term Immobilization with Moderate Confidence in that Assessment*** *Uncertainty Drivers:* • Inventory split between onsite/offsite • Mobility of iodine, technetium, and nitrate to PW and associated confidence in immobilization in vault • Effectiveness of treatment for LDR organics, if needed	***40-45 Years if Executed as Intended with Moderate Technical Risk of Operations*** – *Technical Risks:* • Increased transportation requirements	***High Probability of Successful Project Completion with High Confidence in that Assessment*** *Uncertainty Drivers: None*

[a] Information on the rankings (first score) is provided in Volume I, Appendix A.

CoC = contaminant of concern.
DNF = does not finish.
FBSR = fluidized bed steam reforming.
Hg = mercury.
HLW = high-level wastes.
I = iodine.
LDR = Land Disposal Requirements.
PW = potable water.
Tc = technetium.
TOE = total operating efficiency.

E.3 UNCERTAINTY DRIVERS FOR GROUT ALTERNATIVES

E.3.1 Uncertainties with Long-Term Effectiveness of Proposed Grout Alternatives

The following sections present a series of fact sheets related to the knowledge of key contaminants/ radionuclides present in Hanford low-activity waste (LAW). For each element a summary is given including the inventory in the waste, expected behavior in grout and the subsurface, approaches to improve retention within the waste forms, and the associated uncertainties with disposal. This information was used to support the taxonomy criteria in Section E.4, including the mobility to potable water and confidence in immobilization.

In the subsections below, the inventories presented are based on downloads from the Hanford Best Basis Inventory (BBI) between July 2021 and January 2022. Note that there are uncertainties associated with these inventories, as only a portion of the values are from sampling data of the wastes. Other values come from estimates or from sampling data over several decades. An assessment of data quality of the tank waste data is discussed in Volume II, Appendix B.

E.3.1.1 Iodine Uncertainties

Hanford Waste Background and Inventory

Iodine is present in the Hanford tank wastes as a fission product resulting from historical waste processing (Table E-2). The primary isotope is the long-lived iodine-129 (^{129}I) radionuclide (half-life: 15.7 million years), of which 29.2 Ci (165 kg) is present (based on the BBI updated as of July 2021 and assuming a decay date of July 2015). A poorly quantified inventory of ^{127}I exists for the tanks and has only been quantified in 12 tanks to date (PNNL-31794, *The Removal of Iodine from Liquid Effluents Directed Toward the Effluent Treatment Facility*). Within the tanks, the majority of iodine is expected to be iodide (I^-) (PNNL-30105, *Iodine Speciation Basis and Gap Analysis for Hanford Tank Fam Inventory and During Processing*). Both iodate (IO_3^-) and organo-iodine are possible, and recent work has better speciated and quantified the iodine within the supernatant liquid (Fountain, 2020). An equivalent fraction of iodine is projected to be present in the saltcake (Table E-3), and work in 2020 highlighted for the first time that iodine can be present in the sludge as AgI (Reynolds et al., 2020).

Table E-2. Summary of the Tank Inventory Splits of Iodine-129

Tank Farm	Iodine-129 (Ci)	% Total	200 East or 200 West
A	1.14	4%	E
AN	6.36	22%	E
AP	5.38	18%	E
AW	3.55	12%	E
AX	0.27	1%	E
AY	0.47	2%	E
AZ	0.92	3%	E
B	0.10	0%	E
BX	0.29	1%	E
BY	2.19	7%	E
C	0.01	0%	E
S	2.00	7%	W
SX	1.45	5%	W
SY	1.21	4%	W
T	0.06	0%	W
TX	2.39	8%	W
TY	0.08	0%	W
U	1.52	5%	W
Total	29.37	100%	-

Table E-3. Distribution of Iodine Across the Three Main Phases of Hanford Tank Waste

Tank Phase	Iodine-129
Saltcake	42%
Supernate	45%
Sludge	13%

Iodine is likely to be also present in secondary waste streams generated through vitrification. The iodine is projected to be present on the granular activated carbon (GAC) from the Waste Treatment and Immobilization Plant (WTP) LAW and high-level waste (HLW) vitrification plants, the high-efficiency particulate air (HEPA) filters from both the WTP LAW and HLW Vitrification Facilities, the Ag-mordenite from HLW vitrification, and in the liquid secondary effluents from WTP.

^{129}I levels are used as part of the waste classification in 10 CFR 61.55, "Waste Classification," which is used to classify wastes for near-surface disposal. The Class C limit for ^{129}I is <0.08 Ci/m^3, and the Class A limit is <0.008 Ci/m^3. ^{129}I is also a key radionuclide of interest in the Integrated Disposal Facility (IDF) Performance Assessment (PA) (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*), and ^{129}I is sufficiently mobile in the subsurface that the existing inventory is large enough to impact potable water.

Behavior in Grout Waste Forms and Subsurface

As iodine is most likely to exist as an anion in both its oxidized and reduced forms within the tank waste, little change in behavior is likely between reducing or oxidizing conditions within a grout waste form. The iodine species would be released from the waste form through a similar diffusive process as many other anions. Some evidence exists for partial interactions between iodide/iodate and grout matrices, although the degree of sorption would likely be low. Little is known about the leaching behavior of organo-iodines; however, the expectation would be limited retention as many organic compounds do not interact with grouts similarly to iodide. Within the Hanford subsurface, limited to no natural attenuation has been found once released from the IDF. As such, release rates for ^{129}I leading to projected concentrations at the point of compliance are dictated by waste form performance and release from the IDF. The uncertainty with the behavior of iodine in unmodified grout waste forms or in the subsurface is low compared to other uncertainties with iodine (e.g., inventory partitioning in WTP).

Approaches to Improve Retention

Improved retention of iodine within grout waste forms may be achieved through solubility control and the precipitation of iodine as a low soluble phase. The most common phase being silver iodide (AgI, $K_{sp} = 8 \times 10^{-17}$) (Asmussen et al., 2016; PNNL-26443, *Updated Liquid Secondary Waste Grout Formulation and Preliminary Waste Form Qualification*; RPP-RPT-26725, *Cast Stone Technology for Treatment and Disposal of Iodine-Rich Caustic Waste Demonstration—Final Report*); however, other phases such as bismuth iodide (BiI_3) and lead iodide (PbI_2) can be used (PNL-4045, *Selection of a Form for Fixation of Iodine-129*). In this approach, a getter (or simple chemical form) is used to introduce the precipitating species (e.g., Ag, which is a Resource Conservation and Recovery Act [RCRA]-listed metal) to the liquid waste. Upon forming the stable phase (e.g., AgI), the waste form would be produced and the iodine present in a more stable form within the final waste form. Release of iodine would then be controlled by the stability/solubility of the stable phase. This approach has been successful on the laboratory-scale in suppressing iodine release using >5 wt% of an iodine getter (Ag-zeolite) (Saslow, 2017; RPP-RPT-26725), although tests with minor amounts of getter addition (<0.1 wt%) were not successful in limiting iodine release (PNNL-25577, *Getter Incorporation into Cast Stone and Solid State Characterizations*). No data exists between 0.1 wt% and 5 wt% getter addition to assess thresholds for where iodine retention is acceptable, for the ideal getter loading for performance/economic benefits, or for maintenance of this improvement at field-scale. The solubility approach needs to consider the long-term stability of the precipitated phase and possible interfering mechanisms (e.g., reduction of the cation used, displacement of the iodine by a separate species, competition with a redox getter). The uncertainty with this improvement mechanism lies in the long-term prediction of stability of the phases in disposal site subsurface conditions (for which limited data are currently available) and identifying the optimal getter type and loading. However, geochemical calculations could be used to provide an additional line of evidence.

The removal of iodine can be pursued, and further information is available in Volume II, Appendix C, Section C.15.2. The primary uncertainty with iodine removal is the service lifetime of candidate materials and scale-up of a removal process.

Bulk approaches could also be used for improved iodine retention through enhanced containment (e.g., low permeability or reactive barrier around the waste form) or further isolation within the disposal environment (e.g., larger waste package size reducing the surface area to volume ratio).

Uncertainty Upon Disposal and Mobility to Potable Water

Where an achievable pathway to potable water exists (e.g., Hanford IDF), the long half-life of ^{129}I introduces temporal uncertainty due to the extended timeframes that need to be considered. As covered in taxonomy item 1.1.2 (Volume II, Appendix D), iodine has limited release in 1,000 years but could reach the compliance limits (dependent on inventory/conditions/properties of the waste form) in 10,000 years.

Incorporating sufficient uncertainty in PA modeling around laboratory and short-term data-derived parameters is the best approach to addressing the uncertainties. If a solubility control approach is to be used, then long-term stability of the resulting phase would carry associated uncertainty. Having a better understanding of the stability and release/interference mechanisms of the stable phase would significantly reduce such uncertainty for disposal of the grouted waste form in a site with a pathway to potable water.

Once again, if waste is disposed of at a facility with limited water recharge and inaccessible potable water sources, only the inventory of iodine is a consideration, not the leachability and release, which are only of concern in on-site disposal.

E.3.1.2 Technetium

E.3.1.2.1 Technetium Uncertainties

Hanford Waste Background and Inventory

^{99}Tc is present in the Hanford tank wastes as a fission product and has a long half-life of 211,000 years. There are 25,300 Ci (~1,500 kg) of ^{99}Tc present in the Hanford tank wastes (based on the BBI updated as of February 2022 and assuming a decay date of July 2015). Technetium in the alkaline tank waste (pH >12.5) is primarily present as the oxyanion pertechnetate, $^{99}TcO_4^-$, and with a fraction of poorly quantified (between 0% – 75%) non-pertechnetate that exists in lower oxidation states and usually complexed by organic moieties. The highest inventories of technetium are found in the AN, AP and AW Farm tanks (Table E-4). Due to its soluble nature, the majority of the technetium is present in the saltcake and supernatant liquid (Table E-5). ^{99}Tc supernatant liquid concentrations range from <5E-04 to about 1E-01 µCi/mL (PNNL-23319, *Technetium Inventory, Distribution, and Speciation in Hanford Tanks*, Table A.1).

Table E-4. Summary of the Tank Inventory Splits of Technetium-99

Tank Farm	Technetium-99 (Ci)	% Total	200 East or 200 West
A	6.61E+02	3%	E
AN	4.19E+03	17%	E
AP	3.95E+03	16%	E
AW	3.06E+03	12%	E
AX	2.78E+02	1%	E
AY	4.16E+02	2%	E
AZ	1.64E+03	6%	E
B	1.97E+02	1%	E
BX	3.01E+02	1%	E
BY	1.41E+03	6%	E
C	2.29E+00	0%	E
S	2.01E+03	8%	W
SX	1.33E+03	5%	W
SY	1.74E+03	7%	W
T	1.39E+02	1%	W
TX	2.32E+03	9%	W
TY	8.12E+01	0%	W
U	1.57E+03	6%	W
Total	**2.53E+04**	**100%**	

Behavior in Grout Waste Forms and Subsurface

As pertechnetate, $^{99}TcO_4^-$ is a highly mobile anion in water and in the environment. Therefore, long-term stabilization needed for near-surface disposal of wastes containing ^{99}Tc is a challenge that carries long-term uncertainties.

Table E-5. Distribution of Technetium Across the Three Main Phases of Hanford Tank Waste

Tank Phase	Technetium (Ci)
Saltcake	51%
Supernatant liquid	42%
Sludge	7%

Historically, granulated ground blast furnace slag, currently referred to as slag cement, has been used to achieve both the stabilization of selected anions and cations (e.g., TcO_4^-, CrO_4^{2-}, and Hg^{2+}) and formation of a hydrated waste form matrix (Langton, 1987; Langton and Oji, 2021). Sulfur in the slag glass is responsible for the reducing chemistry that results in precipitation of ^{99}Tc(VII) and other metal anions such as chromate (CrO_4^{2-}) in the alkaline waste solution (Langton, 1987).

The chemistry applied to both removal and in situ immobilization of pertechnetate in Hanford tank waste and Savannah River Site (SRS) tank waste is based on chemical reduction of the pertechnetate Tc(VII) ion to the +4 valance state, Tc(IV). Under sufficiently reducing conditions, TcO_4^- is readily reduced to Tc(IV) and precipitated/immobilized as an oxide, TcO_2, which can be hydrolyzed as a poorly amorphous hydrate, $TcO_2 \cdot nH_2O$, both of which have relatively low solubilities in aqueous solutions and in chemically reducing waste forms such as Cast Stone and saltstone (PNNL-22977, *Characterization of Technetium Speciation in Cast Stone*).

Chemically reduced sulfur species in cementitious material containing slag cement, including Saltstone and Cast Stone, are associated with a dark blue-green color. Oxidation of S(0) and S^- species in air results in a loss of chemical reduction and is associated with a tan to almost white color. This color change is also observed in Cast Stone and Saltstone when samples are exposed to air (SRNL-STI-2012-00468, *Method Evaluation and Field Sample Measurements for the Rate of Movement of the Oxidation Front in Saltstone*). The authors also reported polymeric sulfur (detected by ultraviolet light spectra) in aqueous leachate in contact with the slag-based saltstone. In addition, within 20 minutes after sampling, the polymeric sulfur peak disappeared and no peak for sulfide was observed, which was attributed to rapid oxidation of the leachate in contact with air. Consequently, oxidation and mobilization of low solubility technetium phases is a rapid process when slag-based waste forms are exposed to air; understanding the rate of this process in the disposal environment is imperative (Langton et al., 2014; Chen et al., 2021).

Little is known about the behavior of non-pertechnetate species within grout waste forms. Only a single study exists in which a non-pertechnetate species was placed in a grout waste form and leached (PNNL-23319). There was a small increase in technetium release; however, no spectroscopic evidence of the non-pertechnetate within the grout was provided.

Approaches to Improve Retention

To enhance retention of technetium in cementitious waste forms, several approaches are being considered. Bulk approaches could be used for improved technetium retention through enhanced containment (e.g., low permeability or reactive barrier around the waste form) or further isolation within the disposal environment (e.g., larger waste package size). For example, Saltstone at SRS is disposed of in 32E+06-gallon engineered barriers/robust concrete tanks to achieve a very low surface-area-to-volume ratio and reduce exposure of the waste form to O_2 and moisture. This is the basis of alternatives Grout 5A/5B.

Pacific Northwest National Laboratory (PNNL) and others have investigated technetium getters, which can further stabilize the technetium within a grout waste form. Ideal getters are materials that have specific affinity for Tc(VII) or can react with, bind, and immobilize Tc(VII) in the waste form so that they are resistant to controlling release mechanisms (e.g., oxidation). PNNL has investigated getters as an additive to Cast Stone and also as amendments for backfill in the IDF at Hanford (Asmussen, et al., 2015; Asmussen, et al., 2017; Boglaienko et al., 2019; Burgeson et al., 2011; Pearce et al., 2018; Saslow et al., 2017). Most of the technetium getters tested to date have focused on using reduction-oxidation control to suppress technetium migration; however, ion exchange and incorporation processes have also been studied (PNNL-19681, *Tc-99 Ion Exchange Resin Testing*; Saslow et al., 2018; Bourchy et al., 2022). Additional work is in progress to expand and optimize the performance of technetium getter materials. A thorough examination of methods to improve technetium retention in grout waste forms is provided in SRNL-STI-2020-00228, *Evaluation of Technologies for Enhancing Grout for Immobilizing Hanford Supplemental Low-Activity Waste (SLAW)*. The use of slag as the reducing agent, which converts soluble Tc(VII) to insoluble Tc(IV), was included in all onsite grout Alternatives; however, the use of additional Tc getters was not.

The removal of technetium, as described for alternatives Grout 1C and 2C, can be pursued and further information is available in Volume II, Appendix C, Section C.15.1. The primary uncertainty with technetium removal is the inventory of non-pertechnetate and its impact on removal effectiveness (Section E.3.1.2.2).

Uncertainty Upon Disposal and Mobility to Potable Water

Where an achievable pathway to potable water exists (e.g., Hanford IDF), the long half-life of ^{99}Tc introduces temporal uncertainty due to the extended timeframes that need to be considered. Incorporating sufficient uncertainty in PA modeling around laboratory and short-term data derived parameters is the best approach to addressing this uncertainty. The reoxidation rate of the grout waste form/getter remains the primary uncertainty with long-term disposal at a facility with a pathway to potable water. Measuring the rate of reoxidation in realistic disposal conditions remains the best approach to refine this uncertainty.

Uncertainty also exists in the speciation of ^{99}Tc within the disposed wastes, as the non-pertechnetate fraction may behave differently than pertechnetate within the waste form and within any capture process.

Once again, if disposed of at a facility with limited water recharge and inaccessible potable water sources, only the inventory of ^{99}Tc is a consideration, not the leachability and release.

E.3.1.2.2 Non-Pertechnetate Uncertainties

Hanford Waste Background and Technetium Inventory/Speciation

Speciation of technetium in Hanford tank waste is vital to the management and disposition in grout waste forms. The predominant form of technetium in tank waste is pertechnetate ion, TcO_4^-. There is also a form of technetium in Hanford tank waste known as "non-pertechnetate" (LA-UR-95-4440, *Technetium Partitioning for the Hanford Tank Waste Remediation System: Anion Exchange Studies for Partitioning Technetium from Synthetic DSSF and DSS Simulants and Actual Hanford Waste (101-SY and 103-SY) Using Reillex™-HPQ Resin*), which is believed to be predominantly a Tc(I) carbonyl moiety (LBNL-56315-Ext-Abs, *Investigations to Identify the Soluble, Non-pertechnetate Species in the High-level Nuclear Waste at the Hanford Site*; Lukens et al., 2004), although it may actually be multiple ionic state forms that coexist (PNNL-25000, *Spectroscopic Properties of Tc(I) Tricarbonyl Species Relevant to the Hanford Tank Waste*; PNNL-24916; *Synthesis and Characterization of Tc(I) Tricarbonyl Nitrosyl Species Relevant to the Hanford Tank Waste: FY2016 Status Report*; Chatterjee et al., 2020). The complete speciation and distribution of technetium in Hanford tank waste is not known. Of the 177 Hanford tanks, only 10 have been tested for the presence of non-pertechnetate (PNNL-23319). Whether the non-pertechnetate fraction in waste tanks changed over time is also not known. The presence of non-pertechnetate in specific tanks can potentially be influenced by the presence of complexants in the tank waste and chemistry induced by irradiation of the waste.

Determination of Non-Pertechnetate Species

The initial method used to measure the non-pertechnetate fraction was by processing the waste sample through an ion exchange column that removed only pertechnetate; any remaining technetium in the effluent liquid was called "non-pertechnetate." The purpose of the analysis was to test the effectiveness of various ion exchange resins and as needed, to prepare samples for further decontamination testing and immobilization – not to quantify the amount of non-pertechnetate. Several discrepancies were noted in the ion exchange column data, where results from test to test with samples from the same tank yielded different results. Generally, if <10% of total technetium in a sample was present in column effluent, no further testing or analysis was done to elucidate its speciation or better quantify the exact amount.

Those tanks with <10% of technetium in column effluent could potentially have no non-pertechnetate, but there is no way to know from current test data. Analytical methods, imperfect column packing, slow kinetics, or other experimental issues may have led to some breakthrough of pertechnetate. Most of the tanks that were found to contain >60% non-pertechnetate are "complex concentrate" tanks, or otherwise high organic tanks, which have complex technetium chemistries.

Based on prior quantification of non-pertechnetate in 10 of the 27 double-shell tanks (DST) (using the maximum non-pertechnetate fraction reported) and current estimates in the BBI the non-pertechnetate is approximately 12% of the total technetium in the DSTs (~5% of the total tank waste technetium). A summary of the existing non-pertechnetate data and the impact on the overall technetium inventory is shown in Table E-6. Some of the tanks that have measured non-pertechnetate previously (circa 2000) have since had transfers in/out that may have changed projected concentrations. Note that much of the waste known to contain non-pertechnetate is "complexant concentrate" waste and would likely be best immobilized in the melter anyway because of higher organic content, dependent on the results of contemporary Land Disposal Requirements (LDR) organics studies.

Table E-6. Existing Non-Pertechnetate Data Summary

Tank	Min % non-PT	Max % non-PT	Tc (Ci) - Current BBI	Max Ci non-PT
AN-102	48	80	482	386
AN-103	1.6	8	273	22
AN-107	48	80	302	242
AP-101	0.5	13	738	96
AP-104	69	72	93.6	67
AW-101	0.06	15	468	70
AZ-101	0	0	1310	0
AZ-102[a]	0	0.04	176	0.1
SY-101	53	70	63	44
SY-103	54	78	484	378
			Total (Ci)	1304
			% Tc of Total Tank Waste	5%
			%Tc of DST Tc	13%

[a] Note: A value of 33% non-pertechnetate is present in PNNL-23319, Table 4.7, for Tank AZ-102; however, the reference listed in the table is incorrect. This value could not be confirmed in other available references and is highly suspect.
BBI = Best Basis Inventory. PT = pertechnetate.
DST = double-shell tank. Tc = technetium.

An analysis method for quantifying non-pertechnetate has been developed that is compatible with test procedures used in the 222-S Laboratory (SRNL-STI-2016-00510, *Preliminary Tests for Development of a Non-Pertechnetate Analysis Method*), but the method has not been implemented. Another analysis method has also been developed that uses a special sensor to measure the Tc(I) moiety but would not sense if other forms of non-pertechnetate exist (PNNL-26316, *Non-Pertechnetate Technetium Sensor Research and Development*). A full suite of non-pertechnetate species can be identified using a combination of nuclear magnetic resonance spectroscopy and X-ray adsorption spectroscopy (Chatterjee et al. 2020). Additional information on the topic of non-pertechnetate chemistry is provided in SRNL-STI-2017-00382, *Literature Review of the Potential Impact of Glycolic Acid on the Technetium Chemistry of SRS Tank Waste*).

Non-Pertechnetate Behavior in Grout Waste Forms

The presence of non-pertechnetate species may have significant impacts on potential use of a grout waste form if a significant inventory is present. First, if technetium is to be removed from LAW to enable a grout waste form, most of the known technetium removal methods have only been shown to be effective for the pertechnetate ion. However, removal of a $Tc(I)(CO)_3$ species has been shown using spherical resorcinol formaldehyde resin (Chatterjee et al. 2020). No removal methods have been developed specifically for all of the non-pertechnetate form(s) and only very limited testing has been performed on methods to convert non-pertechnetate to pertechnetate. Second, the target long-term sequestering mechanism for technetium in grout waste forms is insoluble Tc(IV).

Converting to Tc(IV) in the grout forms likely requires that the technetium is originally present as pertechnetate in the waste when mixed with grout-forming materials that contain a reductant. The main source of reductant being blast furnace slag that can convert the Tc(VII) pertechnetate into an insoluble Tc(IV) species (Angus et al., 1985; Langton, 1987; Allen et al., 1997). Once converted into Tc(IV), technetium is present as either an oxide or sulfide species that controls its release from the grout (Lukens et al., 2005; PNNL-20753, *Radionuclide Retention Mechanisms in Secondary Waste-Form Testing: Phase II*; Arai et al., 2015). That reduction-oxidation reaction of Tc(VII) to Tc(IV) with slag is key to sequestering the ^{99}Tc and making it leach resistant (PNNL-25194, *Secondary Waste Cementitious Waste Form Data Package for the Integrated Disposal Facility Performance Assessment*; SRNL-STI-2010-00668, *Long-term Technetium Interactions with Reducing Cementitious Materials*; SRNL-STI-2009-00473, *Geochemical Data Package for Performance Assessment Calculations Related to the Savannah River Site*).

In grout waste forms, whether or not the non-pertechnetate species will undergo this redox conversion is not known, but is considered unlikely because it is already in a reduced oxidation state (i.e., Tc(I) vs. Tc(IV)). Simulant testing of a grout waste form containing a laboratory-synthesized Tc(I) carbonyl complex indicated a ~10× increase in observed diffusivity for a Tc(I) species compared with Tc(VII) (PNNL-24297, E*xtended Leach Testing of Simulated LAW Cast Stone Monoliths*). Although, if this laboratory-synthesized form was identical to the non-pertechnetate in tank waste is not known. Key to the assumptions that underpin grout leaching performance is that the ^{99}Tc is present primarily as Tc(IV) in the grout.

Non-pertechnetate Behavior in On-Site Disposal with Grout

In considering on-site disposal of LAW as a grout waste form, quantification of the non-pertechnetate fraction of the technetium inventory would be needed to accurately project ^{99}Tc fractional release rates from the IDF. A high degree of confidence in the inventory between the technetium forms in tanks and measurement of their corresponding release mechanisms from grout would ensure that the risk associated with disposal of the non-pertechnetate inventory in an on-site scenario can be accurately assessed.

Because it is not known how much non-pertechnetate is present in tanks and whether it would be sequestered in a grout waste form similar to pertechnetate; at this time, there is associated uncertainty in selecting on-site disposal of a grouted waste form. If found that there is sufficient non-pertechnetate present and it is not sequestered, this fraction of technetium released from the waste forms could increase the overall IDF source term. Similarly, selecting the flowsheet alternative where technetium removal is performed prior to grouting may result in a grout that contains the non-pertechnetate fraction, which is not removable by known methods. The contribution to overall fractional release from the IDF in this scenario is unknown and could only be determined with improved quantification of the non-pertechnetate fraction in the tanks. Note that the uncertainty around non-pertechnetate behavior is captured in the risk budget analysis performed to support taxonomy criteria 1.1.2, where all technetium was assumed to be mobile in the conservative case. However, a mitigation to the non-pertechnetate scenario could be sending the tanks with high non-pertechnetate (e.g., Tank AN-102, AN-107) to the LAW melter, and those with low or no non-pertechnetate to grout in a sample-and-send approach.

The risk and consequences of non-pertechnetate in on-site disposal cannot be quantified until: (1) a precise analytical method is implemented, and a quantitative study is performed on actual (fresh) tank farm samples, (2) actual leachability of non-pertechnetate in grout is measured, (3) PA calculations are performed on the results of these two studies, and, if needed, (4) a practical conversion method is developed.

Non-pertechnetate Behavior in Off-Site Disposal with Grout

However, if disposal of the grout waste form is not dependent on the long-term technetium leaching performance, the presence of non-pertechnetate species is likely inconsequential. If the waste form is disposed offsite, where a potable water path is not plausible and the insoluble property of technetium in grout is not a fundamental assumption or requirement, the non-pertechnetate inventory and chemical reactions do not impact the disposal. The majority of the technetium from the tanks would still have limited solubility in the waste form because it would convert from the majority pertechnetate in the waste to the majority insoluble Tc(IV) in the waste form. Further, the non-pertechnetate may have unexpected reactions that render it insoluble, and its leachability would be partially mitigated by the limited porosity of the waste form. So off-site disposal of the waste form is considered to be plausible regardless of the presence of non-pertechnetate.

Non-pertechnetate Behavior in Vitrification and Fluidized Bed Steam Reforming

For vitrification and FBSR, disposal of non-pertechnetate in a final glass or mineralized waste form is not an issue. The heat of the melter or FBSR will convert any non-pertechnetate to pertechnetate when it reaches 600°C (Luksic et al., 2019), which would happen in the cold cap or DMR. Although there may be some differences in vapor retention, its behavior in the disposed waste form is the same as the technetium that originated as pertechnetate in the waste.

E.3.1.3 Selenium-79 Uncertainties

Hanford Waste Background and Inventory

Selenium-79 (^{79}Se) is present in the Hanford wastes as a fission product resulting from historical waste processing. There are 114 Ci (1.6 kg) of ^{79}Se present in the Hanford wastes (based on the BBI updated as of July 2021 and assuming a decay date of July 2015). The concentration of ^{79}Se varies by tank and by phase within the tank, with a maximum inventory in Tank AN-101 (5.38 Ci); the ^{79}Se inventory is split with 55% of the inventory located in the 200 East Area tanks and 45% in the 200 West Area tanks. A summary of the farm distribution is provided in Table E-7. Direct sampling data is available for only 24 of the 177 Hanford tanks for ^{79}Se. Little is known about the speciation of ^{79}Se within the tanks, which will likely exist as some form of oxyanion. The ^{79}Se is assumed to have even distribution across the sludge, saltcake, and supernatant liquid in the tanks.

Table E-7. Summary of the Tank Inventory Splits of Selenium-79

Tank Farm	Selenium-79 (Ci)	% Total	200 East or 200 West
A	3.6	3%	E
AN	20.0	18%	E
AP	12.9	11%	E
AW	7.2	6%	E
AX	1.7	2%	E
AY	1.5	1%	E
AZ	4.0	3%	E
B	0.2	0%	E
BX	0.9	1%	E
BY	11.1	10%	E
C	0.0	0%	E
S	13.1	11%	W
SX	8.3	7%	W
SY	5.5	5%	W
T	0.2	0%	W
TX	13.8	12%	W
TY	0.2	0%	W
U	9.5	8%	W
Total	**1.14E+02**	**100%**	

^{79}Se was projected to partition mainly to the LAW glass in the 2017 IDF PA (RPP-RPT-59958), with a range of 108 Ci – 140 Ci partitioning to the glass, the overall ^{79}Se inventory estimates having decreased from 144 Ci to 114 Ci. Table E-8 provides the projected splits. The remainder was projected to partition to the Effluent Treatment Facility (ETF) and only a small fraction to the solid secondary waste. Note that this behavior is uncertain, as selenium has been identified as being volatile in melter conditions (ORP-53935, *Redox Control for Hanford HLW Feeds VSL-12R2530-1, Rev.* 0). However, the partitioning will not impact the overall assessment of limited impact to potable water due to the low inventory.

Table E-8 provides a summary of the distribution of ^{79}Se between the main waste streams in the IDF PA. Case 7 is considered the "base case" with high retention of radionuclides and contaminants with recycle, and Case 10A is a contrived case with an extremely low retention of ^{99}Tc in the glass.

Table E-8. Distribution of Selenium-79 Between the Main Waste Streams

Waste Stream	IDF PA[a] Case 7 (Ci)	IDF PA[a] Case 10A (Ci)
LAW glass	140	108
ETF liquid secondary waste	2.85	35.3
Solid secondary waste	0.005	0.004

[a] RPP-RPT-59958, 2018, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*, Rev. 1, Washington River Protection Solutions, LLC and INTERA, Inc., Richland, Washington.

Note: the 2017 IDF PA assumed ~144 Ci of Se-79 while recent projections are 114 Ci.

ETF = Effluent Treatment Facility. LAW = low-activity waste.
IDF = Integrated Disposal Facility. PA = performance assessment.

^{79}Se is not included as part of the waste classification in 10 CFR 61.55. ^{79}Se was not a major radionuclide of interest in the IDF PA; however, information on ^{79}Se was included.

Behavior in Grout Waste Forms and Subsurface

There is little information to date on the behavior and speciation of selenium within grout waste forms. However, as selenium will likely exist as an oxyanion across oxidation state under alkaline conditions, the selenium would likely be mobile and thus a conservative assumption could be made in PA modeling. A study of selenium speciation and leaching within candidate grouts would help reduce or eliminate this uncertainty. Within the Hanford subsurface, there is likely limited to no natural attenuation of selenium, and a low distribution coefficient (K_d) <1 has been assumed in the past (PNL-10379, *Distribution Coefficient Values Describing Iodine, Neptunium, Selenium, Technetium and Uranium Sorption to Hanford Sediments*).

Approaches to Improve Retention

With the lack of data, there are also no documented approaches to improve selenium retention in grout waste forms (if needed). Bulk approaches could be used for improved selenium retention through enhanced containment (e.g., low permeability or reactive barrier around the waste form) or further isolation within the disposal environment (e.g., larger waste package size to reduce the surface area to volume ratio).

Uncertainty Upon Disposal and Mobility to Potable Water

The primary uncertainty around ^{79}Se during disposal conditions lies with the lack of experimental data to date and the inventory estimates to be disposed. Where an achievable pathway to potable water exists (e.g., Hanford IDF), the long half-life of ^{79}Se introduces temporal uncertainty due to the extended timeframes that need to be considered. With the lack of site-specific data, uncertainty must be built into any PA modeling. However, there is only a small amount of ^{79}Se in the Hanford tanks, and any migration to potable water is unlikely to exceed regulatory limits (Section E.3.1.9) and projected to be on the order of zepto-curie concentrations (10^{-21}Ci/L).

If waste is disposed of at a facility with limited water recharge and inaccessible potable water sources, only the inventory of ^{79}Se is a consideration, not the leachability, release, and transport. Since the inventory is extremely low, there is minimal risk from ^{79}Se in on-site or off-site disposal.

E.3.1.4 Resource Conservation and Recovery Act Metal Uncertainties

Hanford Waste Background and Inventory

The RCRA metals (i.e., Ag, As, Ba, Cd, Cr, Hg, Pb, and Se) have a range of origins within the Hanford tank wastes. (Note that ^{79}Se is addressed in Section E.3.1.3 and is separately considered versus the hazardous non-radioactive Se isotopes discussed here.) These RCRA metals play a key role in waste acceptance as their performance in the U.S. Environmental Protection Agency (EPA) Method 1311 test (Toxicity Characteristic Leaching Procedure [TCLP]) is used from a regulatory perspective to demonstrate satisfactory treatment for land disposal restrictions (LDR); and to date, waste forms containing blast furnace slag pass the TCLP. Table E-9 shows the inventory currently projected across all tanks based on the BBI (updated as of February 2022 and assuming a decay date of July 2015) and the distribution of RCRA metals as a weight percentage (wt%) within the tank farms (Table E-10). The data in Table E-10 indicates that chromium (546,000 kg total) and lead (73,300 kg total) represent the majority of the total mass of RCRA metals across all tanks. The distribution indicates that the majority of metals are contained within a few tank farms (e.g., S Farm tanks for Cr, and AN, B, and T Farms for lead).

Table E-9. Inventory of RCRA Metals in Hanford Tanks

Constituent	Inventory[a] (kg)
Cr	546,000
Pb	73,300
Ba	4,090
As	4,070
Cd	2,310
Ag	3,410
Hg	1,820
Se	3,720

[a] Inventory as of February 2022 and current as of the July 2015 decay date in the Hanford Best Basis Inventory.

Table E-10. Distribution (as % of total) of the RCRA Metals Across the Hanford Tank Farms

Tank Farm	Pb	Ba	As	Cd	Ag	Hg	Cr	Se
A	6%	5%	0%	1%	2%	17%	2%	0%
AN	24%	8%	18%	25%	8%	11%	5%	19%
AP	6%	0%	2%	1%	12%	8%	4%	6%
AW	2%	4%	9%	4%	35%	1%	3%	8%
AX	1%	2%	0%	3%	0%	1%	1%	0%
AY	2%	10%	1%	5%	6%	2%	1%	1%
AZ	2%	3%	0%	0%	0%	1%	1%	0%
B	11%	8%	2%	3%	1%	4%	2%	2%
BX	6%	3%	5%	19%	2%	8%	3%	0%
BY	6%	14%	8%	13%	4%	7%	11%	10%
C	0%	0%	0%	0%	3%	0%	0%	0%
S	2%	8%	12%	3%	9%	4%	16%	14%
SX	2%	9%	15%	9%	5%	15%	18%	18%
SY	3%	3%	3%	6%	1%	1%	15%	4%
T	11%	12%	2%	3%	6%	1%	2%	2%
TX	6%	0%	1%	0%	0%	4%	8%	1%
TY	2%	3%	0%	0%	0%	13%	1%	0%
U	8%	7%	22%	5%	6%	1%	8%	15%

RCRA = Resource Conservation and Recovery Act.

Table E-11 shows the distribution of the RCRA metals between the three primary tank waste phases. Although the speciation of the RCRA metals within the tanks is not well characterized, lead, barium, silver, and mercury are believed to be primarily present as insoluble oxides/hydroxides in the sludge, while arsenic, chromium, and selenium are projected to be primarily oxyanions in the saltcake and supernatant liquid. The speciation and distribution are further complicated, as many of the RCRA metals could form complexes with organic components of the waste. Complexation may explain why cadmium exists in all three waste phases – as hydroxides in the sludge and as soluble complexes in the saltcake and supernatant liquid.

Table E-11. Distribution (as wt% of total) of the RCRA Metals Across the Waste Phases in the Hanford Tanks

Waste Phase	Pb (kg)	Ba (kg)	As (kg)	Cd (kg)	Ag (kg)	Hg (kg)	Cr (kg)	Se (kg)
Saltcake	21%	33%	64%	43%	23%	7%	67%	62%
Supernate	4%	3%	14%	20%	8%	0%	7%	17%
Sludge	75%	64%	22%	37%	69%	92%	26%	22%

Ag = silver. Cd = cadmium. Pb = lead.
As = arsenic. Cr = chromium. Se = selenium.
Ba = barium. Hg = mercury.

Behavior in Grout Waste Forms and Subsurface

Most of the RCRA metals exist primarily in one or two oxidation states. Of these metals, chromium is the most likely to change oxidation states from relatively insoluble Cr(III) to soluble Cr(VI); therefore, chromium may act as a sentinel species for the potential for reduction-oxidation impacts within grouted waste forms. Note that silver and barium exist only in a +1 state and would not be expected to be influenced by reduction-oxidation changes.

No direct speciation of RCRA metals in the tank wastes, except for chromium, have been recorded. In a reducing grout waste form, the RCRA metals would be projected to be in their lowest oxidation states (e.g., Cr(III), Pb(II), As(III), Cd(I), Hg(I)). The alkaline conditions of the waste forms also promote insolubility of metals as hydroxides. Under the conditions of unaged grouted waste forms, the potential release of the RCRA metals, based on TCLP test, shows that reducing waste forms consistently pass the TCLP (PNNL-22747, *Supplemental Immobilization of Hanford Low Activity Waste: Cast Stone Screening Tests*). Under oxidizing conditions, some RCRA metals (e.g., Cr) could oxidize to more mobile species, increasing their release behavior. However, the impact of oxidation on the behavior within the subsurface would be highly dependent on the RCRA metal and its speciation.

Approaches to Improve Retention

All evidence to date shows that grout waste forms pass TCLP for the RCRA metals (PNNL-22747; PNNL-26570, *Effluent Management Facility Evaporator Bottoms: Waste Streams Formulation and Waste Form Qualification Testing*); therefore, there is little need for specific amendments to target these metals. However, if enhanced retention is required, improvements would be metal-specific and there is likely no catch-all approach for improved retention.

Additionally, approaches to enhance retention for one constituent may impact the release of another. For example, the use of a silver-based getter for iodine retention provides excess silver, which may potentially lead to different silver leaching behavior from waste forms than would be expected with the nominal amount of silver in the waste. However, note that the impact of silver-containing getters for iodine on the release of silver from grouted materials is not well-defined.

Bulk waste disposal approaches, such as the grout disposal unit (GDU) suggested for improved retention of other contaminants, would also be effective for RCRA metals and through enhanced containment (e.g., low permeability or reactive barrier around the waste form) or further isolation within the disposal environment (e.g., larger waste package size to reduce the resulting surface area to volume ratio).

Uncertainty Upon Disposal and Mobility to Potable Water

Regardless of the disposal facility considered, waste acceptance criteria relative to RCRA metals will be based on performance in the TCLP test, where chemical stabilization has typically shown to be sufficient (PNNL-22747). Where a pathway for leachate to reach potable water exists (e.g., Hanford IDF), the long-term chemical changes of the waste form (e.g., carbonation, oxidation) may facilitate increased release and potential transport to potable water. For the cases where a silver-containing getter is used in the waste form for iodine retention, the corresponding release behavior of excess silver is not well documented; however, the studies that have measured silver release show low release rates (PNNL-28545, *Development and Characterization of Cementitious Waste Forms for Immobilization of Granular Activated Carbon, Silver Mordenite, and HEPA Filter Media Solid Secondary Waste*).

E.3.1.5 Nitrate/Nitrite Uncertainties

Hanford Waste Background and Inventory

Nitrate and nitrite are nonradioactive, inorganic anions present in Hanford wastes due historical waste processing activities (Table E-12).

Table E-12. Summary of the Tank Inventory Splits of Nitrate and Nitrite

Tank Farm	NO_3 (kg)	% Total	NO_2 (kg)	% Total	200 East or 200 West
A	5.74E+05	1%	3.69E+05	3%	E
AN	4.44E+06	9%	2.39E+06	20%	E
AP	4.47E+06	9%	2.00E+06	17%	E
AW	3.18E+06	6%	1.51E+06	13%	E
AX	3.21E+05	1%	1.74E+05	1%	E
AY	4.28E+05	1%	2.05E+05	2%	E
AZ	5.52E+05	1%	5.35E+05	4%	E
B	1.69E+06	3%	1.32E+05	1%	E
BX	1.34E+06	3%	1.36E+05	1%	E
BY	5.19E+06	10%	6.07E+05	5%	E
C	1.66E+03	0%	1.07E+03	0%	E
S	7.08E+06	14%	6.78E+05	6%	W
SX	4.72E+06	9%	8.79E+05	7%	W
SY	9.83E+05	2%	5.33E+05	4%	W
T	5.79E+05	1%	8.66E+04	1%	W
TX	1.11E+07	22%	8.49E+05	7%	W
TY	5.66E+05	1%	4.71E+04	0%	W
U	3.72E+06	7%	7.48E+05	6%	W
Total	5.09E+07	100%	1.19E+07	100%	

In general, these two anions form the background liquid phase of the tank wastes, although precipitated nitrogen may be found in the solid phase as nitrates and nitrites depending on the reduction-oxidation conditions of the waste. Nitrite (NO_2^-) may be converted to nitrate (NO_3^-) via oxidation; however, the reaction is kinetically hindered (i.e., time-dependent). The NO_3 and NO_2 ratio relative to hydroxide is crucial in corrosion control in the tanks. In general, the concentration of nitrates is in stoichiometric ratio with the amount of sodium in solution. Nitrate/nitrite are not regulated under RCRA, and no release limits for NO_3^- or NO_2^- are available.

EPA recognizes nitrate and nitrite sources from land application of fertilizers and has published maximum contaminant levels, enforceable for public water systems, at 10 mg N/L and 1 mg N/L for NO_3^- and NO_2^-, respectively (EPA, 2022).

Behavior in Grout Waste Forms and Subsurface

Due to the solubility of many nitrate minerals, chemical retention of NO_3^- and NO_2^- in grouted waste forms and in subsurface environments is limited. Most sorption surfaces are negatively charged at neutral to alkaline conditions; therefore, anions, like NO_3^- and NO_2^-, are not attracted to these surfaces. In grouted waste forms, a small and likely insignificant fraction of nitrate may be substituted into some secondary precipitation minerals (e.g., ettringite) (Hailong, 2021). Geochemical speciation of Cast Stone porewater suggests that the majority of nitrate is contained in the porewater of cold test samples (Chen et al., 2021). Therefore, the pore structure of grouted materials offers the primary physical retention of nitrogen due to a disconnected, tortuous pore pathway – the longer and more tortuous the pathway, the slower the release. However, implementation and maintenance of these physical approaches is limited to date to slow nitrate/nitrite release.

Crucial to the behavior of nitrate and nitrate is the understanding of their subsurface behavior, primarily the impact of denitrification. Denitrification is a microbiological process that involves the multi-step reduction of NO_3 to NO_2 and then to gaseous nitrogenous products. Denitrifying microbes are ubiquitous in sedimentary environments, including industry and nuclear waste impacted sites. Numerous laboratory studies and field demonstrations have used the inherent denitrifying capacity of subsurface environments for in situ remediation of NO_3 and co-contaminants, including at the Hanford Site, Oak Ridge Reservation, and other nuclear waste disposal sites around the world (PNNL-28846, *Carbon Tetrachloride: Evaluation of Biotic Degradation Mechanisms and Rates*; Lloyd et al., 2005; Safonov et al., 2018; Wu et al., 2010). As an anaerobic process, denitrification activity will the highest in low O_2 regions (natural or engineered) of the subsurface; however, denitrifying bacteria survive well in aerobic conditions.

Nitrate is a widespread contaminant at the Hanford Site stemming from past nuclear production activities and waste disposal practices (DOE/RL-2010-89, *Long-Range Deep Vado se Zone Program Plan*). Under the neutral to slightly alkaline subsurface water conditions present at the Hanford Site, nitrate displays no effective adsorption to sediments. The primary attenuation processes that affect nitrate include subsurface water flow (dilution), abiotic reduction by reactive mineral phases, and microbial degradation. While the bulk of the Hanford subsurface is influenced by oxic conditions, ample evidence shows that chemically reduced, anaerobic zones do comprise a portion of the total aquifer volume. These zones represent “hot spots” for abiotic and microbial activities that have an important impact on potable water at the site.

The conceptual site model for contaminant attenuation in the 200 West Area aquifer (Central Plateau Area) includes abiotic reduction and microbial degradation occurring in anoxic, reduced zones of low permeability (e.g., silt and clay lenses, Lower Ringold Mud Unit, Cold Creek Unit). There are numerous indicators that these zones exist and that degradation pathways are actively occurring for nitrate/nitrite, and for other priority contaminants (e.g., carbon tetrachloride, chloroform, and reduction-oxidation active radionuclides) (PNNL-28846; Neeway et al., 2019; PNNL-29999, *Evaluation of Ammonia Discharge into PUREX Crib 216-A-37-1 and Nitrogen Species Fate in the Subsurface*). Reliable indicators for contaminant (NO_3) reduction include site subsurface water data, characterization studies, remedy evaluations, and laboratory-based investigations (PNNL-28846; Lin et al., 2012; PNNL-29999; Yan et al., 2016).

Approaches to Improve Retention

Since there is little chemical retention for nitrates/nitrites, the principal methodologies for improving the overall retention of NO_3^- and NO_2^- is to: (1) limit exposure to a leaching solution, and (2) provide a longer diffusion pathway and smaller surface area for release (e.g., reduced porosity). Infiltration control through caps and other barriers can limit the volume of leaching solution in contact with grouted waste forms. Getters are unlikely to be successful to improve nitrate retention (SRNL-STI-2020-00228).

Recent work with geopolymers has shown promise for improved nitrate retention with lower salt solution (VSL-21R15000-1, *Development of Improved Grout Waste Forms for Supplemental Low Activity Waste Immobilization*). Maximization of diffusion path and minimization of exposed surface area are best achieved by creation of bulk solidified materials.

Uncertainty Upon Disposal and Mobility to Potable Water

The principal sources of uncertainty upon disposal include the amount of water infiltration in contact with the waste form and the potential for attenuation and dilution of leached NO_3^- and NO_2^- between the waste form and the point of compliance. Disposal environments that minimize infiltration (e.g., through barriers or discontinuous pathways) are more likely to retain NO_3^- and NO_2^- from grouted waste forms. Peak concentration of nitrate and nitrite scale linearly to disposed inventory and therefore, any off-site disposal with confirmed "no-release" conditions are good disposal candidates with respect to nitrate and nitrite retention.

E.3.1.6 Land Disposal Restrictions Organics Uncertainties

An overview of the existing knowledge behind LDR organics can be found in Volume II, Appendix A, Section A.3.6. In summary, several recent analyses have provided groundwork for confirming the presence/absence of LDR organics in the Hanford wastes, their concentrations relative to non-wastewater standards in the liquid and immobilized forms, and their removability via treatment (e.g., evaporation, chemical treatment) through historical analyses, recent tank samplings, updated analytical methodology, and degradation assessments. These efforts, including those occurring during the NDAA21 Section 3125 study timeline, have reduced the uncertainty associated with the possibility of LDR organics exceeding compliance limits in a grouted waste form.

The assessments of LDR organics carry varying levels of uncertainty. For the quantification of LDR organics, much of the sampling data for the tanks is over 30 years old. Identification of compounds in the tank waste has relied heavily on headspace data where uncertainty can arise from Henry's Law concentration conversions in the tank waste. A summary of the organics and associated samplings is provided in the waste profiles in Volume II, Appendix B. The stability of the LDR organics in the tank waste also raises uncertainty in their concentrations as some LDR organics suspected to be present in the Hanford tanks may have degraded (chemically or radiolytically) while in storage in the tanks or have become affected by tank transfers. Updated sampling of the tank wastes can address the uncertainty associated with their presence and concentration in the tanks. Additional work is needed to determine what, if any, LDR organics could be formed through decomposition of more complex organics in the tank wastes. In the analysis of historical process knowledge from the Hanford Site, some LDR organics can be eliminated from the candidate list in the tank waste, with high certainty, because there is no history of select LDR organics being used in the Hanford mission and the specific organic compound could not be formed in the tank waste.

Some of the LDR organics may have detection limits that are above the corresponding target non-wastewater standard in the tank waste measurements using contemporary analytical techniques, while other compounds have never been analyzed for (for example, phthalic acid, a likely decomposition product from phthalates in the tanks). Efforts are ongoing to evaluate alternate techniques to improve the quantification and lower detection limits to below the non-wastewater limits and develop methods for other compounds. Achieving detection limits significantly below the non-wastewater limits would remove the uncertainty around the risk of an LDR organic exceeding compliance levels based solely on noncompliant detection limits. If these discrepancies between detection limits and target concentrations remain, treatment (e.g., evaporation, chemical oxidation, directed to vitrification) may be pursued or a variance evaluated for the organic. Evaporation has been evaluated as a means to remove LDR organics that may be present above compliant levels, and further work is ongoing to confirm the efficacy of the evaporation approach to such organics.

Organics not removed by evaporation may be destroyed by chemical oxidation (e.g., permanganate treatment), although there is uncertainty around the efficacy of the process for specific organics and the resulting impact on a grouted waste form.

However, with the low concentrations of many of the potential LDR organics, there is high confidence that a chemical treatment process could be successful, if required. The cost of implementing a separate chemical oxidation treatment from evaporation was believed to be within the projected cost uncertainty already considered. In addition, the work underway in evaluating LDR organics in tank waste is expected to conclude a fraction of tank waste does not require LDR organic pretreatment prior to grouting. DOE will need to establish the treatment facility waste acceptance criteria with stakeholders that results in identifying the parameters and constituents to be used in determining whether LDR organic pretreatment is required for a campaign/batch of waste before treatment.

E.3.1.7 Vault Design Uncertainties

Uncertainty around mobility to potable water of key contaminants is still present in alternatives Grout 5A, 5B and 6, where a GDU is used for disposal. However, this uncertainty is lessened compared to containerized options as a monolith in an engineered vault that limits interaction with the environment, creates long transport pathways, and slows the rate of change of waste form properties controlling release. The extent of this effect is dependent on vault size. These uncertainties can be further improved with an updated PA of a GDU design at Hanford, the last being performed in 1993 (WHC-SD-WM-EE-004, *Performance Assessment of Grouted Double Shell Tank Waste Disposal at Hanford*).

E.3.1.8 Sample and Send Uncertainty

For alternatives Grout 1D and Grout 6, an additional uncertainty exists in the projected splits of the supplemental LAW inventory that will be directed onsite to the IDF versus to an off-site disposal facility. These splits directly impact the projected impact to potable water onsite, as a near linear relationship between inventory and peak dose exists in the IDF (dictated by waste form concentration). If off-site pathways are not available or minimally used, the uncertainty is similar to the on-site cases (Grout 1A, Grout 2A). This uncertainty can be handled by evaluating inventory sensitivity cases in the IDF PA.

E.3.1.9 Confidence in Immobilization with Respect to Potable Water and Mobility to Potable Water

To assess the mobility of the radionuclides and contaminants to a potable water source, conservative qualitative estimates of full system waste form release were made using the IDF PA risk budget tool and using volumetric concentrations of the various species within the waste forms to project peak groundwater concentration in different inventory and performance cases. The inclusion of radionuclides in the IDF PA risk budget tool was developed based on an agreement between DOE and the Washington State Department of Ecology to include radionuclides for information only and does not imply that radionuclides are regulated under the IDF RCRA permit. DOE uses the information on radionuclides from the IDF PA risk budget tool to perform analyses that are consistent with its capabilities (e.g., inventory and waste form release rate sensitivities) and are necessary under the IDF PA maintenance program required by DOE M 435.1-1, *Radioactive Waste Management Manual*.

E.3.1.9.1 Inventory Uncertainty

Two inventory cases were tested for this full system: ***one where the best case retention of radionuclides/ contaminants in the LAW glass was assumed, and one where the worst case retention of radionuclides/ contaminants in the LAW glass was assumed*** (Table E-13). The “best case” glass retention was assumed using the splits from Case 7 of the IDF PA (RPP-RPT-59958), where the majority of contaminants/ radionuclides are retained in the glass.

The "worst case" glass retention used values from Case 10A of the IDF PA, where large amounts of contaminants/radionuclides are partitioned to the secondary waste grout. In each case, the supplemental LAW inventory was unchanged. The releases from all waste forms can be combined qualitatively. The "SLAW" cases assume the supplemental LAW inventory is ~44% of the total inventory then the best and worst glass case splits were applied to the remaining "first LAW" glass inventory. The uncertainty within the inventory splits will be refined once WTP begins operations.

Table E-13. Inventory Splits Evaluated to Technetium, Iodine-129, and Selenium-79

Species	Stream	Best Glass Retention- Case 7 from IDF PA[a]	Worst Glass Retention – Case 10 from IDF PA[a]	Best Case Glass Retention + SLAW[b] Disposed of in IDF	Worst-Case Glass Retention + SLAW[b] Disposed of in IDF
Tc	ILAW	99.50%	31.91%	55.30%	17.70%
	SLAW	-	-	44.4%	44.4%
	ETF LSW	0%	67.80%	0%	38%
	SSW	0.08%	0.05%	0%	0%
	Melter	0.14%	0.04%	0%	0%
^{129}I	ILAW	56.21%	19.43%	31.25%	10.80%
	SLAW	-	-	44.4%	44.4%
	ETF LSW	0.22%	63.80%	0.12%	35.47%
	SSW	41.23%	14.91%	22.92%	8.29%
	Melter	0.08%	0.02%	0.04%	0.01%
^{79}Se	ILAW	97.92%	75.00%	48.96%	37.50%
	SLAW	-	-	50%[c]	50%[c]
	ETF LSW	0.13%	0.10%	0.06%	0.05%
	SSW	1.99%	24.51%	0.99%	12.26%
	Melter	0%	0.02%	0%	0.01%
NO_3	ILAW	0%	0%	0%	0%
	SLAW	-	-	44.4%	44.4%
	ETF LSW	0.29%	3.98%	0.16%	2%
	SSW	0%	0%	0%	0%
	Melter	0%	0%	0%	0%
Cr	ILAW	82.94%	77.77%	46.11%	43.24%
	SLAW	-	-	44.4%	44.4%
	ETF LSW	0.00%	5.83%	0.00%	3.24%
	SSW	0.13%	0.12%	0.07%	0.07%
	Melter	0.13%	0.11%	0.07%	0.06%

[a] RPP-RPT-59958, 2019, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*, Rev. 1, Washington River Protection Solutions, LLC and INTERA, Inc., Richland, Washington.

[b] Using the supplement LAW inventories from the Integrated Flowsheet (RPP-RPT-57991, *One System River Protection Project Integrated Flowsheet*, Table 6-7, comparing the volumes of treated LAW (col 41a) sent to WTP to the volumes of LAW for supplemental treatment (col 45+46).

[c] No split for ^{79}Se was provided for supplemental LAW so a 50% split was presumed. Differences from 100% totals result from splits to other streams

ETF = Effluent Treatment Facility.
IDF = Integrated Disposal Facility.
ILAW = immobilized low-activity waste.
LAW = low-activity waste.
LSW = liquid secondary waste.
PA = performance assessment.
SLAW = supplemental low-activity waste.
SSW = solid secondary waste.
WTP = Waste Treatment and Immobilization Plant.

The "SLAW" cases assume the supplemental LAW inventory listed in the System Plan (ORP-11242, *River Protection Project System Plan*, Rev. 8), then the best and worst glass case splits were applied to the remaining "first LAW" glass inventory. ^{99}Tc, ^{129}I and ^{79}Se were evaluated. There is uncertainty within the inventory splits that will be refined once WTP begins operations.

E.3.1.9.2 Risk Budget Evaluation

The inventory splits were then used to calculate concentrations of radionuclides within the various waste streams in Ci/m^3. Peak dose is presumed to scale linearly to the concentration of radionuclide within that set volume of waste. By adjusting the projected volumetric concentrations to actual amounts in the risk budget tool "locked volume", a qualitative peak dose could be calculated.

For example:

- In the risk budget tool, an inventory of 26,368 Ci of technetium is present for 278,797 m^3 of LAW glass, giving a peak concentration of 93.5 pCi/L, assuming a fractional release rate of 2.57E+07 yr^{-1}. This split would equal 0.095 Ci/m^3.
- Using the best case splits for Grout 1A, the supplemental LAW grout is projected to have 0.0219 Ci/m^3.
- This concentration would equal 6,106 Ci of technetium in 278,797 m^3 of glass listed in the risk budget tool.
- The value of 6,106 Ci was input to the risk budget tool, and the resulting peak dose was ~21 pCi/L.
- The peak dose was then adjusted for the volume of glass in the alternative to be ~10 pCi/L.

The same approach was used for the ETF liquid secondary waste.

For the solid secondary waste, a similar approach was taken, but using the individual splits for the solid secondary waste types. The technetium was only evaluated for the HEPA filters, the ^{129}I was evaluated for GAC and AgM, and the ^{79}Se for the HEPA filters and ion exchange based on the splits used in the IDF PA.

To determine the release from the supplemental LAW grout, three waste form release rate cases were evaluated to capture uncertainty around waste form performance.

- Using the projected volume of supplemental LAW grout from the System Plan (ORP-11242, Rev. 8) (320,489 m^3) and the Ci distribution, a volumetric concentration was determined.
- The volumetric amount was then applied to the evaluation system of choice:
  - ***Conservative Case*** – The "conservative case" uses the risk budget tool values for grout performance (liquid secondary and solid secondary waste types) and the supplemental LAW grout performance was calculated using the ETF grout. The ETF grout is assumed to be oxidized from Day 1 in the risk budget tool and is therefore considered to be highly conservative. The peak dose determined using the 18,900 m^3 volume in the risk budget tool was multiplied by 17× to account for the increase in volume for the supplemental LAW grout.
  - ***Back Calc*** – The "back calc" case uses the minimum fractional release rate determined in PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility* (Table S.1). To do this, the LAW glass line in the risk budget tool was used for the calculation, the fractional release rate was adjusted, and a volume factor of 1.14 was used to estimate peak dose.

– ***Improved Case*** – The "improved case" uses a best case for the grout system (reduced for technetium, getter continues to hold for iodine) added to the supplemental LAW grout. To do this, the LAW glass line in the risk budget tool was used for the calculation, and a factor of 1.14 was used to estimate peak dose. The fractional release rate was decreased by several orders of magnitude to account for the improved waste form performance.

The qualitative results of the assessment were used to draft the taxonomy assessments in Volume II, Appendix D, Section 3.1.1.2 of each alternative.

E.3.2 Risks in Mission Duration and Technical Risks of Operations for Grout Alternatives

The primary uncertainty driver in the implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration) (C2) criteria for the grout alternatives (Grout 4A, Grout 4B and Grout 6) that carried a "moderate" rating is the increased risk brought forward by the increased transportation of waste. A description of the transportation uncertainties and risk is provided in Volume II, Appendix H. In summary, the risk is driven by closure of the transport route following a theoretical spill. While the probability of a spill occurrence is very low, there are high unmitigated consequences and high schedule impacts.

During the study questions around uncertainty pertaining to maintaining off-site disposal access for the duration of the mission were raised. This scenario is unlikely and did not drive uncertainty rankings. Further discussion of the scenario is given in Volume I, Section 4.0.

E.3.3 Uncertainties Associated with Likelihood of Project Successful Completion for Grout Alternatives

None of the grout alternatives had a rating beyond "low uncertainty" for the likelihood of successful mission completion (including affordability and robustness to technical risks) (C3), primarily due to the extensive experience in the implementation of grouting or low temperature processes for waste immobilization/stabilization. Volume II, Appendix L describes the prior experience drawn upon in this assessment.

E.4 UNCERTAINTIES IN LIFECYCLE COSTS

A full description of the development of the lifecycle costs is provided in Volume II, Appendix F. Based on the assessment, cost uncertainties can range from -20% to 100% on the projected cost.

E.5 UNCERTAINTIES IN VITRIFICATION ALTERNATIVE

The National Defense Authorization Act for FY 2017 (NDAA17) report (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*), Appendix B, covered many of the uncertainties associated with LAW vitrification at Hanford, with little change in that assessment since. The primary uncertainty drivers in the long-term effectiveness (environmental and safety risk after disposal) (C1) criterion are similar to the on-site grout alternatives due to the presence of secondary waste grout waste forms in the IDF. The uncertainties with those waste forms are identical to those discussed in Section E.3, with the main caveat being secondary wastes will likely have a higher concentration of radionuclides/contaminants (dependent on partitioning in WTP) than a primary grout waste form. High uncertainties are present in the partitioning of iodine and mercury (Volume II, Appendix B, Section B.3.1). Two waste forms with similar properties but different concentrations will see a higher overall release from the waste form with higher concentration. These uncertainties upon disposal would be mitigated with off-site disposal of the secondary waste.

The primary LAW glass waste form also carries uncertainty with effectiveness. The release of radionuclides and contaminants from the LAW glass is predicted using the immobilized low-activity waste (ILAW) corrosion model, which is based on Transition State Theory (RPP-RPT-59958). Extensive work was undertaken in recent years to understand the applicability of the ILAW corrosion model to enhanced waste LAW glass compositions and assess conservatism in the current approach.

The common assumption is: as waste loading is increased in the glass, durability will be sacrificed to a degree. Further information on these efforts is provided in:

- Nava-Farais et al. (2021), "Applying Laboratory Methods for Durability Assessment of Vitrified Material to Archaeological Samples"
- PNNL-28999, *Alternative Approaches to Determining K_g and Modeling its Influence on ILAW Glass Corrosion*
- PNNL-31072, *Stirred Reactor Coupon Analysis: Determination of Glass Composition Effects on Forward Rate Model Parameters*
- PNNL-31746, *Ion-Exchange Immobilized Low-Activity Waste Glass Rate Model Term*
- PNNL-31758*, FY2021 Report: ILAW Glass Stage II and III Static Dissolution Testing and Modeling*
- VSL-21R4960-2, *FY2021 ILAW Glass Ion-Exchange Rate Testing.*

An example of the uncertainty arising from this emerging information is the influence of the ion-exchange process in glass corrosion. The ion exchange process will control glass dissolution over the majority of its life-time upon disposal. A presumed conservative assumption was made in the LAW glass corrosion model where a constant ion exchange rate was used when evidence exists that the ion exchange rate will decay exponentially with time. In turn, the release from the glasses would overestimate release with the use of a constant term. Recent work (PNNL-31746; VSL-21R4960-2) has identified a time-dependent ion exchange rate model that can be used. Implementation of this time-dependent ion exchange term only led to a 10× decrease in predicted release in IDF waste form simulations (PNNL-31746).

As with any application of model theories to long-term performance, there are uncertainties associated. One such discrepancy exists in comparing the contribution of LAW glass to peak dose of ^{99}Tc. In the 2003 Risk Assessment (RPP-17675, *Risk Assessment Supporting the Decision on the Initial Selection of Supplemental ILAW Technologies)*, the peak concentration of technetium from WTP glass was 0.771 pCi/L (Table 4-8b of RPP-17675), while in the 2017 IDF PA (RPP-RPT-59958, Rev. 1) the peak ^{99}Tc concentration (base case) was 90 pCi/L (Table 5-43 of RPP-RPT-59958). These differences highlight uncertainties associated with primary waste form behavior in the IDF.

The implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration) (C2) criteria carried technical risks of operations. There was an identified risk of delays due to annual operating costs exceeding the projected budget. This risk was described in the NDAA17 report (SRNL-RP-2018-00687) and in Volume II, Appendix F. The increased radiation and chemical exposure risks were attributed to the volatilization of radionuclides and harmful chemicals (mercury) transferring them to the offgas management system, and the frequent worker exposure required for regular consumable (bubblers, melters, HEPA) replacements. The large volume of wastewater discharged, ~2-3 gallons per gallon of LAW feed, and the corresponding large volume of secondary wastes, both liquid and solid, contributed to the environmental technical risks.

For the likelihood of successful mission completion (including affordability and robustness to technical risks) (C3), vitrification had low uncertainty associated with the low probability assessment due to mitigation by experience gained from future operations with WTP LAW melters.

E.6 UNCERTAINTIES IN FLUIDIZED BED STEAM REFORMING

The NDAA17 report (SRNL-RP-2018-00687), Appendix D, covered many of the uncertainties associated with the use of fluidized bed steam reforming (FBSR) for Hanford LAW. The primary uncertainty drivers in the long-term effectiveness (environmental and safety risk after disposal) (C1) criterion are driven by the identification of the FBSR waste form and the limited amount of site-specific data on representative waste forms, which can be considered similar to the on-site grout alternatives. The dissolution data available compares the granular FBSR product to representative LAW glass; however, the test data available does not correlate directly to a value used in a PA. The corrosion results are promising, as in similar tests (e.g., product consistency test, single-pass flow-through) the normalized dissolution rates of the FBSR granular product are within the ranges of normalized dissolution rates for borosilicate glass with compositions within the processable compositions of Hanford's WTP (PNNL-14805 *Waste Form Release Data Package for the 2005 Integrated Disposal Facility Performance Assessment*; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063, *Chemical Composition and PCT Data for the Initial Set of Hanford Enhanced Waste Loading Glasses*; PNNL-28838, *Enhanced Hanford Low-Activity Waste Glass Property Data Development: Phase 2*), but further testing is needed to produce rate model parameters to represent the dissolution of this waste form in a PA to calculate a fractional release rate.

The implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration) (C2) criteria for FBSR carried technical risks of operations. There was an identified risk of delays due to technical issues and annual operating costs exceeding the projected budget. These two risks were described in in the NDAA17 report (SRNL-RP-2018-00687). The increased radiation and chemical exposure risks were attributed to the volatilization of radionuclides transferring them to the offgas management system and aerosolization of dust and toxic gases. The frequent worker exposure required for regular consumable (e.g., nozzles, HEPA) replacements was also identified as a risk. The high volume of clay and other granular solids, liquid oxygen, and nitrogen, each having unique transport mechanisms, increased worker exposure risk.

For the likelihood of successful mission completion (including affordability and robustness to technical risks) (C3), FBSR had low uncertainty associated with the low probability assessment due to prior experience with WTP. Note that in alternative FBSR 1B, the carbonate product was not considered as this resulting product (used at the Integrated Waste Treatment Unit [IWTU]) would only have minor changes to the taxonomy criteria related to previous demonstration of the technology, while uncertainties related to waste form performance would persist.

Table E-14 summarizes other relevant unknowns pertaining to the FBSR alternatives.

Table E-14. Fluidized Bed Steam Reforming Uncertainties and Potential Mitigations

Uncertainty	Potential mitigations
During pilot-scale demonstration testing or facility startup, FBSR may not achieve at least 50% TOE, especially in the first 3 operating years when the feed vector is highest.	• Slow the feed rate during the first 3 operating years; for example, extending the first 3 years of operation to 4 years would match a TOE of about 33%. Beyond the first 3 years of the feed vector, the TOE can be lower than 50% and still meet the feed vector rate. • Increase lag tank storage • Increase the size of the treatment facility (only practical if done prior to final design/construction) • Evaluate and solve the issue(s) that limit the TOE
During pilot-scale demonstration testing or facility startup, FBSR may not be able to achieve the design basis feed rate.	• Slow the feed rate during the first 3 operating years; for example, extending the first 3 years of operation to 4 years would match a TOE of about 33%. Beyond the first 3 years of the feed vector, the TOE can be lower than 50% and still meet the feed vector rate. • Increase lag tank storage • Increase the size of the treatment facility (only practical if done prior to final design/construction) • Evaluate and solve the issue(s) that limit the feed rate
A refractory lining may be needed for the DMR.	• This will be determined in detailed design; including or excluding a refractory lining would have a small (negligible) cost impact
Partitioning of ^{99}Tc and ^{129}I to spent carbon may be higher than can meet IDF acceptance requirements.	• Move the offgas scrubber upstream of carbon bed Hg sorption • Improve Tc/I retention in grouted spent carbon and filter waste forms • Send spent carbon to off-site disposal
Pilot-scale demonstration testing may show that a wet scrubber for ^{99}Tc and ^{129}I may not be needed to achieve the needed capture in the primary waste form.	• Remove the wet scrubber from the design, which would simplify the process and lower costs
Certain unit operations may fail to operate as intended.[a]	• Perform more representative and extensive pilot testing than was done for IWTU
For FBSR 1A, disposal of monolith waste form in IDF: During demonstration testing, the waste form may fail to meet IDF performance requirements.	• Modify additives and stoichiometries to achieve a waste form that meets IDF performance requirements • Proceed with FBSR 1B (disposal offsite at WCS)
For FBSR 1B, disposal of waste form at WCS: Texas blocks WCS from accepting Hanford wastes.	• Negotiate with Washington, Texas, or secure disposal options (e.g., HIC to IDF)
For FBSR 1B: Public opposition to transportation halts rail shipping.	• Change route, shift to road/truck shipping, or secure other disposal options

[a] During IWTU startup and operation, several unit operations (including the DMR fluidizing gas distributors, feed nozzles, process gas filters, and granular product handling system) required redesign and re-demonstration. This occurred when pilot-scale testing was not representative or extensive enough to identify certain issues that were only found on IWTU startup.

DMR = denitration and mineralizing reformer.
FBSR = fluidized bed steam reforming.
Hg = mercury.
HIC = high integrity container.
I = iodine.
IDF = Integrated Disposal Facility.
IWTU = Integrated Waste Treatment Unit.
Tc = technetium.
TOE = total operating efficiency.
WCS = Waste Control Specialists, LLC.

E.7 MINOR UNCERTAINTIES CONSIDERED BUT NOT DRIVERS

Throughout the assessments, several other uncertainties were identified; however, they did not become drivers of the overall assessment. These items are acknowledged in the written taxonomies and are summarized here. These items were considered minor as they could be closed with minimal effort or upon processing start, or would not affect the overall performance of the alternative if changed.

Grout facility engineering uncertainty – While the exact design of the grout facility(ies) associated with the alternatives is not known, an assumption was made that the flowsheet and approach would be similar to that used at SRS. This uncertainty in design was deemed minimal due to the expansive experience in producing grout waste forms using a variety of approaches (discussed in Volume II, Appendix L). Alterations to facility design were not expected to impact alternative efficiency or resulting waste form performance.

Inventory uncertainty in tanks – Much of the data available on the inventory in the Hanford tanks is based on estimates built on sampling data from other tanks. When coupled with analytical uncertainties in a complex matrix like the tank wastes, there is uncertainty in the overall inventories present. However, this uncertainty was deemed minimal due to improved sampling in recent years and the range of values considered as possible partitions between waste streams/disposal sites.

Ammonia release – Ammonia release is identified as a risk/uncertainty in the assessment arising from the treatment of secondary wastes and long-term stability/release from waste forms. Because first LAW melters will produce a large volume of ammonia regardless, any additional ammonia from one of the supplemental LAW alternatives was deemed to be of minimal additional consequence.

Supplemental LAW feed vector – A summary of the uncertainties associated with the supplemental LAW feed vector is provided in Volume II, Appendix B, Section B.4.

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Appendix F. Cost Estimates, Mission Model Results, and Associated Assumptions

F.1 INTRODUCTION

This appendix addresses the cost estimates that were developed for the various low-activity waste (LAW) supplemental treatment process alternatives for the Hanford Site to provide for comparisons between the process alternatives. The appendix also includes TOPSim modeling of the overall Hanford tank waste mission. This modeling was performed to reflect the mission impacts of LAW supplemental treatment.

F.2 COST ESTIMATE DEVELOPMENT

F.2.1 Low-Activity Waste Supplemental Treatment within the Hanford Tank Waste Mission

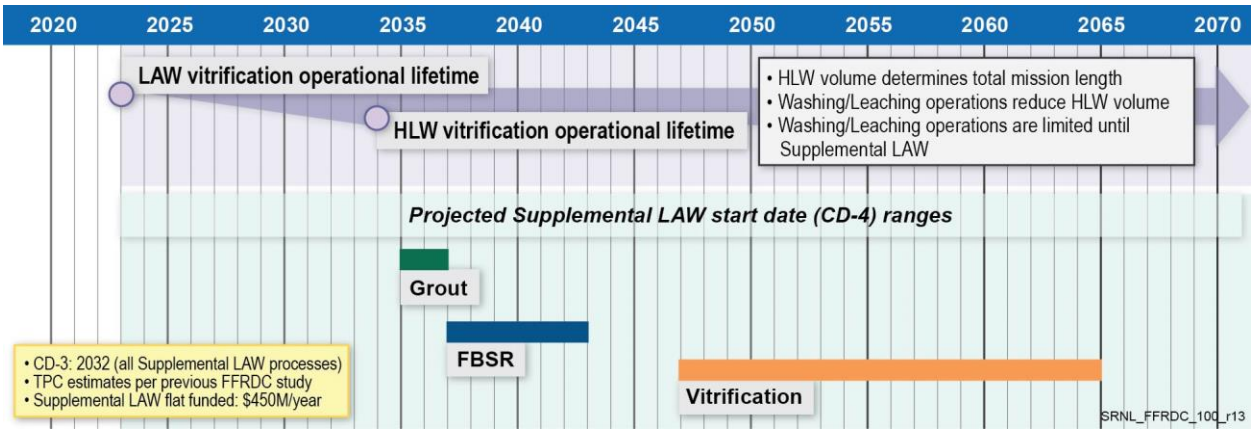
Cost estimates were generated in a manner consistent with U.S. Department of Energy (DOE), Office of Legacy Management reporting to allow for comparisons of the alternatives with respect to LAW supplemental treatment capital and operating expenses and as part of the overall tank waste processing mission. Input data on the capital costs, operations, and equipment/consumables were obtained for the alternatives provided as part of the National Defense Authorization Act for fiscal year (FY) 2017 (NDAA17) study (SRNL-RP-2018-00687, 2019, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*). These "point" data were then incorporated on an annualized project/mission estimating spreadsheet to evaluate the alternatives and their integration into the tank waste clean-up mission. This was accomplished by adapting the facility and operations estimates onto a project timeline to compare alternative cost and schedule. Costs identified in this section are presented as FY 2023 constant-year dollars, unless otherwise noted. Cost from external sources are presented as unescalated dollars, and some figures and tables also show unescalated costs to facilitate direct comparison with cost estimates generated in other publicly available reports such as the mission cost and schedule profiles independently generated by the Washington River Protection Solutions (WRPS) Mission Integration Analysis group.

LAW supplemental treatment alternative technologies include vitrification, fluidized bed steam reforming (FBSR), and grout. The alternatives terminate via on-site (vitrification, FBSR, and grout) disposition and/or off-site (FBSR and grout) disposition pathways. All alternatives assume direct-feed low-activity waste (DFLAW) vitrification as the initial and preferentially fed LAW process option. The DFLAW process is assumed to start in 2023 and continues throughout the tank waste mission.

High-level waste (HLW) vitrification was likewise assumed for all alternatives. HLW vitrification was assumed to start at the end of calendar year 2033. Consistent with the majority of recent studies pertaining to optimizing the River Protection Project (RPP) mission (ORP-11242, *River Protection Project System Plan*, Rev. 6 onward), HLW vitrification is assumed and modeled to pace the overall mission schedule. LAW supplemental treatment is often described as providing the bulk waste processing capacity needed to support maximum efficiency of HLW vitrification. The interplay between LAW supplemental treatment, the availability and usage of double-shell tank (DST) space, and HLW vitrification therefore reflect important facets of the various alternatives, well beyond a simple comparison of point estimate costs.

The interplay between LAW supplemental treatment alternatives and the overall RPP tank waste mission is graphically introduced in Figure F-1. This figure provides a timeline reflecting the target start-up dates for LAW and HLW vitrification and a range of dates reflecting potential start dates for the LAW supplemental treatment facilities. The LAW supplemental treatment facility start-date ranges are projections based on the point estimates generated in the FFRDC NDAA17-3134 report. These dates are also consistent with the need to minimize potential impact to the start-up of HLW vitrification. To that point, work towards Critical Decision (CD)-3 was assumed to initiate on or about 2032.[1]

[1] Alternatives that do not require primary (grout/vitrification/FBSR) facilities avoid this limitation (and cost) – namely Grout 4A and Grout 4B.



Note that the facility construction timing will minimize expense during the upcoming start-up of LAW vitrification (DFLAW) and the completion and start-up of HLW vitrification.

Figure F-1. Comparison of Projected Operational Start Date Ranges Based on Low-Activity Waste Supplemental Treatment Facility Cost and Complexity

A funding level of $450 million per year throughout construction and operations was used as a benchmark for comparison.[2] This benchmark budget was used to determine the duration of the construction phase for each alternative. Activities required before the initiation of construction, such as preliminary design approval, project baseline, and contracting, were assumed to require no less than 3 years, even if the benchmark budget would support an earlier start.

Figure F-2 shows the range of possible construction start times for each primary technology when annual construction expenditures are limited to $450 million. Note that the range for vitrification is considerably wider than for FBSR, which is wider than for grouting. These differences are specifically due to the nature of the point estimates, which were provided as Class 5 with a projected uncertainty range of -10% to +100%; therefore, the $7,500 million construction estimate for vitrification ranges from $6,750 million to $15,000 million. At the high end of that range, a $15 billion plant would not be operational until about 2065, while the lower end value is consistent with a 2047 start of operations. This highlights both the considerable uncertainty in the point estimates and the dependence of both schedule and mission completion on facility cost. Using the same logic for grouting and FBSR facilities, the point estimates reflect ranges of start dates as 2035 to 2037 (grout) and 2037 to 2043 (FBSR).

Figure F-2 provides a linkage of the potential mission completion dates with and without LAW supplemental treatment and as a function of the LAW supplemental facility start-up dates. System planning modeling efforts, somewhat analogous to those employed by DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC&WM EIS) (and associated Reader's Guide and Summary, and Cost Report [DOE/ORP-2003-14]), indicate that without LAW supplemental treatment, the tank waste mission could potentially extend well beyond 2090, facilitating the potential need to replace the Waste Treatment and Immobilization Plant (WTP) complex at least once. Likewise, Figure F-2 illustrates the linkage between facility cost/startup projection date plus the integration within and the impact to the overall tank waste mission.

The tank waste cleanup mission is paced by vitrification of the tank waste sludge portion via the HLW Vitrification Facility. HLW vitrification requires feed preparation to increase solids content and remove a large fraction of the soluble sodium salts – the very volume that is delivered to the LAW Vitrification Facility and to LAW supplemental treatment for processing and disposition.

[2] Annual average funding of $450 million was selected by the FFRDC team as a benchmark for this analysis. This figure does not imply a budgetary limit recommendation or prediction, and the results of the comparison of alternatives did not prove to be sensitive to the specific benchmark chosen.

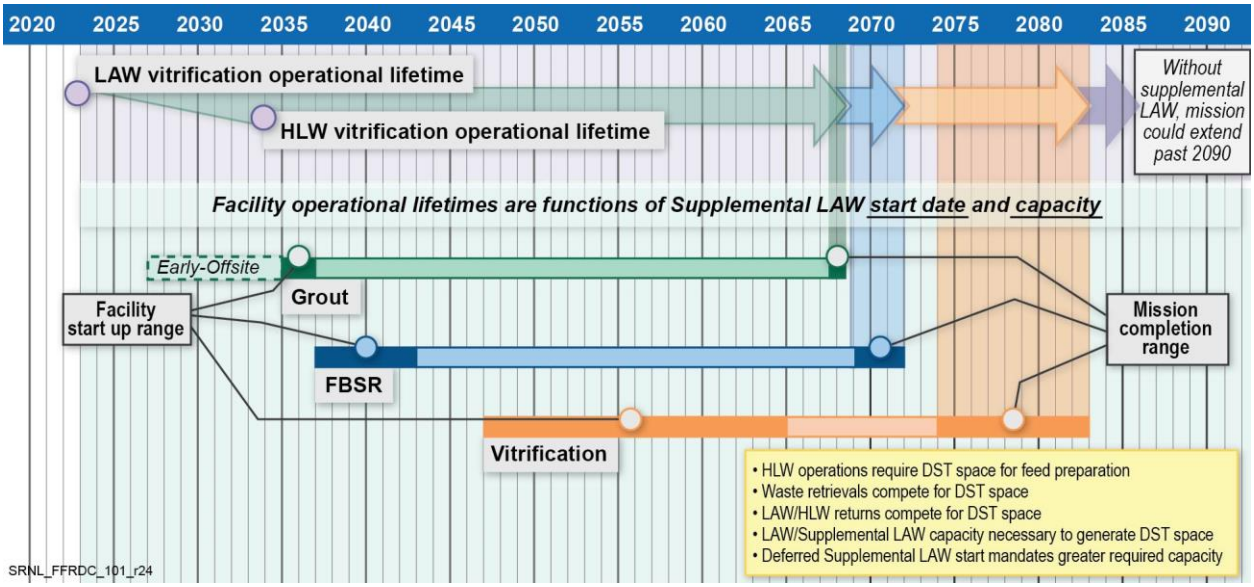


Figure F-2. Relationship Between Low-Activity Waste Supplemental Treatment Start Date and Projected Tank Waste Mission Completion Date Ranges

HLW feed preparation requires processing capability and DST space. DST space is also required to consolidate and store the incoming volume from single-shell tank (SST) retrievals. Further, space is required to store HLW vitrification effluent and integrate that volume via feed preparation and LAW processing. All of these actions must be integrated with production capability and rates. The focus of LAW supplemental treatment is to increase the work-off rate of the tank waste volume to support the overall retrieval/storage/preparation system capacity – allowing HLW vitrification to effectively pace the RPP clean-up mission. Per Figure F-2, LAW supplemental treatment operations are assumed to be unconstrained by either feed preparation or funding.

Figure F-2 illustrates this point as the timeline links the projected start-up dates for various LAW supplemental treatment processes, with the concordant impact to the overall processing mission schedule. Based on the modeling results from previous work (and consistent with the results summarized in the TC&WM EIS [DOE/EIS-0391]), HLW vitrification, when operational, is significantly limited without the supporting capability provided by LAW supplemental treatment. A rough assessment indicates that the HLW Vitrification Facility will be limited to one-half throughput—in other words, every 2 years of HLW facility operations without LAW supplemental treatment adds 1 year back to the overall mission (MR-50638, *Analysis of Alternatives (AoA) Scenario Alternative 18 Phased Startup*, and MR-50713, *NDAA LAWST Modeling Study*). Constraining the start-up dates of LAW supplemental treatment (as a function of project cost and schedule) will therefore significantly impact the completion date for waste treatment. As the LAW supplemental treatment dates are a function of facility cost, higher facility costs imply a later starting date (and larger range thereof), more HLW vitrification years at lower capacity, and a longer total mission duration with concordantly higher cost. Conversely, if LAW supplemental treatment can be facilitated without large projects, pre-2035 start dates would allow use of available DST space for feed preparation (LAW and HLW) and to support retrievals.[3]

[3] See alternatives Grout 4A (off-site grout with on-site disposition), Grout 4B (off-site grout with off-site disposition), and Grout 6 (a hybrid alternative assuming off-site grout with off-site disposition through 2039 and on-site grout with on-site disposition from 2040 on).

F.2.2 Low-Activity Waste Supplemental Treatment Alternatives Mission Cost Profiles

Recognition of the relationship between facility cost, mission capability, and mission completion allows for better clarity when evaluating alternatives. More importantly, as the feed vector for LAW, HLW, and LAW supplemental treatment did not include the WTP Pretreatment (PT) Facility as a process facility (but did not preclude it), the cost, timing, and mission implications of each process alternative can be more readily and realistically evaluated.[5]

The LAW supplemental treatment technology was placed onto a project timeline based on cost and projected start date (DOD-2017-0018, *Inflation and Escalation Best Practices for Cost Analysis: Analyst Handbook*). Point estimates for facility cost, operations, equipment replacement, plus research and development (R&D), were taken from the NDAA17 study (SRNL-RP-2018-00687) and adapted to the spreadsheet on an annual basis (unescalated). An escalation factor was applied for each year as the project progressed. Annual funding required for the project was determined against the escalated cost and any funds remaining from the flat funding basis were carried over – remaining with the project. The mission schedule and completion year were interpolated using Figure F-2. This exercise was performed for each alternative.

For readers less familiar with the technical terminology of cost/benefit analysis, the following reviews the various different kinds of "dollars" described in this report, and how each is used.

- **Unescalated dollars**, also known as ***constant-price or current dollars***, express costs in terms of today's prices for goods and services. Most project cost analyses begin with an estimate in unescalated dollars. Because DOE typically sees prices grow faster than in the general economy, unescalated dollars tend to understate future costs.
- **Escalated dollars**, also known as ***budget dollars*** or ***then-year dollars***, adjust for the fact that prices for goods and services change over time. This change is a combination of general inflation (i.e., changes in the purchasing power of a dollar) in the economy and industry-specific real price change above or below the rate of general inflation. DOE publishes guidance on escalation assumptions to be used by cost analysts.[4]
- **Constant year dollars**, also known as ***real dollars*** or ***inflation-adjusted dollars***, correct for the effect of general inflation in the economy so that the purchasing power of a dollar is the same in all years. In general, if adding costs across multiple years, constant year dollars should be used.
- **Discounted dollars**, also known as ***present value*** (PV), account for the time value of money and the time preferences of consumers. An inflation-adjusted dollar next year is worth less than an inflation-adjusted dollar today because it is possible to invest that dollar today to have more than a dollar next year. Also, the public generally prefers to receive benefits sooner rather than later, other things being equal.

DOE project management guidance recommends 2.4% annual escalation be reflected in operating cost estimates (DOE, 2021).[6] This guidance also allows for 3.8+% escalation to be applied against large, unique capital projects. Note that large, unique facilities such as those comprising WTP may reflect even higher escalation. Therefore, a sensitivity range was developed by applying 2.4% escalation for operations (OPEX) and either 4% (base case) or 8% (sensitivity analysis) escalation for the development and construction of the primary LAW supplemental treatment facilities (CAPEX).[7]

[4] In general, neither escalated nor unescalated dollars should be added across multiple years because their value is not constant over time. This analysis provided some totals in escalated or unescalated dollars to allow for direct comparisons against past RPP mission totals, but the FFRDC team used only constant year dollars and present value in assessing the alternatives.

[5] Pretreatment via tank-side cesium removal (TSCR) was assumed for all alternatives throughout the RPP mission. A singular value of $15/gal (unescalated) was selected based on TOPSim modeling and imposed to provide a basis for alternative (grout/vitrification/FBSR) comparison versus attempting to create multiple small capital projects across the mission scope. This basis is derived from (1) the estimate of $8.5 million annual OPEX cost (MR-50713, this study) for 1.2 Mgal of TSCR processing (just over $7/gal), plus (2) an estimate of $1.1 million per crystalline silicotitanate (CST) ion exchange column (two per changeout) against 200,000 gallons per batch ($11/gal), for an aggregate cost of $18/gal. The cost of CST per gallon will significantly decrease as SST saltcake is processed – to approximately 600,000 gallons per batch (less than $4/gal). Nominally three-fourths of the feed will be saltcake derived versus supernatant liquid – leaving a homogenized cost between $12 and $13/gal. This value was rounded up to $15/gal.

[6] 2.4% was used in the lifecycle cost (TOPSim examples) model results (MR-50638, MR-50713) – for CAPEX and OPEX.

[7] The use of 8% escalation was chosen specifically to provide a sensitivity range. Actual escalation per the WTP (the best known analog) is difficult to interpret due to programmatic changes but appears significantly higher than 4% based on the TC&WM EIS (DOE/EIS-0391).

A set of mission planning spreadsheets specific to each LAW supplemental treatment alternative was created for this study to allow internal comparisons between the various alternatives. Illustrations of this methodology are provided in Table F-1 through Table F-9. To construct the cost profiles shown in those tables, constant price funding profiles were first escalated to produce then-year budget dollar requirements, then deflated to produce constant year dollar annual amounts that could be compared against the $450 million benchmark annual budget. Inflation was assumed to be 2.1% annually based on Congressional Budget Office long-range projections (CBO, 2021).

The Vitrification 1 alternative presented a challenge to this methodology because both capital and OPEX projections exceeded what could be executed within the benchmark average funding level, even permitting carryover of unspent funds from year to year. Constraining capital expenditures to the benchmark budget would result in a 2050 start of supplemental LAW treatment. To keep up with HLW processing, the escalated annual OPEX costs at that point in time would exceed the benchmark budget by more than $200 million/year (shown in Table F-1). Calculations show that annual average funding of ≈$555 million beginning in 2023 would be needed to escrow sufficient funds to complete the treatment mission, with unspent funds from the construction period covering a substantial portion of the operating costs. To the extent that this kind of carryover of funds might not be feasible, annual operating expenses would be even higher.

To evaluate sensitivity, Table F-3 reflects execution of the vitrification capital project at the -10% low end of the estimate range. The benchmark budget would then allow for the facility to be completed by 2047 with 2048 radioactive operations, but projected operations costs would still exceed the benchmark budget, requiring ≈$550 million per year. Conversely, were capital project costs to fall at the high end of the estimate range, or to experience escalation of 8%, the vitrification project would be further delayed and require significantly greater funding. Table F-4 summarizes these sensitivities.

Project spreadsheets were also prepared for the FBSR and Grout alternatives (Table F-5 through Table F-9). Based on the point estimate facility costs, the nominal projected facility startups are 2039 for FBSR and 2035 for Grout 1 (A, B, and C), 2 (A, B, and C), and 5A. Alternatives Grout 4 (A or B) do not require an on-site grouting facility and the hybrid Grout 6 alternative delays facility startup to the end of 2039. The off-site capability for Grout 4 and Grout 6 alternatives starts up in 2027 (in the southwest quadrant). In addition to the primary processing facilities, a LAW feed evaporator (LFE) is shown for the FBSR and grout alternatives to support operations – plus those of the existing LAW Vitrification Facility.[8]

Rough-order-of-magnitude (ROM) R&D activities were also included for project costing. The pilot projects estimated for FBSR and vitrification per the NDAA17 report (SRNL-RP-2018-00687) assumed on-site 10th-scale pilot efforts of integrated systems – WTP LAW vitrification, HLW vitrification, and pretreatment, plus LAW supplemental treatment FBSR or vitrification. For this study, the piloting activity is assumed to be performed at an off-site vendor with system capability, and the pilot expense is shown at about a quarter of the previous estimate. Based on technical team input, the R&D reflected for the vitrification alternative was also adjusted down to the same total as for the FBSR (≈$600 million).

FBSR 1A (on-site production and disposal in the Integrated Disposal Facility [IDF]), Grout 4B (off-site grout production and off-site disposition), Grout 1A (on-site grout production with on-site disposal in IDF), and Grout 6 (the hybrid option of off-site grout/disposition through 2039 followed by on-site grout with vault disposition) were selected for display, in addition to the aforementioned Vitrification 1. Example project spreadsheets are provided for these alternatives in Table F-1 through Table F-9.

Summary key cost data – total unescalated cost and escalated cost at 4% and 8% for the primary capital projects – for all alternatives is shown in Table F-10 (Section F.2.2.6).

[8] Note the feed evaporator was not added to the Vitrification 1 project spreadsheet as one is already included in the infrastructure package planned for supporting HLW processing – which happens at or near the same time (≈2050). This is also consistent with the LAW supplemental treatment Vitrification 1 (modified) TOPSim run (MR-50638).

Table F-1. Example Project Cost and Funds Planning Sheet for Alternative Vitrification 1

Benchmark Funding Level ($450 million/year) Consistent with Facility Completion But Not Operations

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	...	2075
T&D Plus Pilot Activity funded with capital project	50	75	100	125	130	75	50																					
Conceptual Planning /Approve Mission Need - CD-0	$10																											
Conceptual Design / Acquisition Strategy - CD-1		$20	$20																									
Preliminary Design / Performance Baseline - CD-2				$50	$75	$100																						
Definitive Design / Approve Start of Construction - CD-3							$150	$175																				
Procurement / Long-Lead Procurement							$125	$275	$400	$400	$250	$150	$50															
Construction									$100	$150	$200	$300	$350	$400	$400	$450	$450	$450	$300	$300	$300	$250	$50					
Startup / Cold Commissioning - CD-4																						50	$175	$225	$350			
Hot Commissioning / Operations (OPEX)																										$515		$515
FY Cost (Unescalated)	$60	$95	$120	$175	$205	$175	$325	$450	$500	$550	$450	$450	$400	$400	$400	$450	$450	$450	$300	$300	$300	$300	$225	$225	$350	$515		$515
Cum Cost (Unescalated)	$60	$155	$275	$450	$655	$830	$1,155	$1,605	$2,105	$2,655	$3,105	$3,555	$3,955	$4,355	$4,755	$5,205	$5,655	$6,105	$6,405	$6,705	$7,005	$7,305	$7,530	$7,755	$8,105	$8,620		$22,350
Escalation Factor	1.08	1.12	1.17	1.22	1.27	1.32	1.37	1.42	1.48	1.54	1.60	1.67	1.73	1.80	1.87	1.95	2.03	2.11	2.19	2.28	2.37	2.46	2.56	2.67	2.77	1.90		3.43
FY Cost (Escalated @ 4%)	$65	$107	$140	$213	$259	$230	$445	$640	$740	$847	$720	$749	$693	$720	$749	$877	$912	$948	$657	$684	$711	$739	$577	$600	$970	$977		$1,768
Cum Cost (Escalated)	$65	$172	$312	$525	$784	$1,015	$1,460	$2,100	$2,840	$3,687	$4,407	$5,157	$5,849	$6,570	$7,319	$8,195	$9,107	$10,055	$10,712	$11,396	$12,107	$12,846	$13,423	$14,023	$14,993	$15,970		$51,783
Funding Level (Annual)	$469	$479	$489	$499	$510	$520	$531	$543	$554	$566	$577	$590	$602	$615	$628	$641	$654	$668	$682	$696	$711	$726	$741	$757	$772	$789		$1,326
Cumulative Funding	$469	$948	$1,437	$1,936	$2,446	$2,967	$3,498	$4,041	$4,594	$5,160	$5,738	$6,327	$6,929	$7,544	$8,171	$8,812	$9,466	$10,134	$10,816	$11,512	$12,223	$12,949	$13,690	$14,446	$15,219	$16,007		$42,132
Funding (Overage/Shortfall)	$404	$776	$1,125	$1,411	$1,662	$1,952	$2,038	$1,941	$1,754	$1,473	$1,330	$1,171	$1,080	$974	$852	$616	$359	$79	$103	$116	$116	$102	$267	$423	$225	$37		($9,651)
																												($442)
Second LAW Vit Cost - $7.5B in FY 2023 $	Region of DFLAW plus HLW Completion and Start-Up																											
Equivalent*	$ 469	$ 479	$ 489	$ 499	$ 510	$ 520	$ 531	$ 543	$ 554	$ 566	$ 577	$ 590	$ 602	$ 615	$ 628	$ 641	$ 654	$ 668	$ 682	$ 696	$ 711	$ 726	$ 741	$ 757	$ 772	$ 789		$ 1,326
Start 2025 - spend 10% by 2032			Flat Funding		$ 450		1.18	1.21	1.23	1.26	1.28	1.31	1.34	1.37	1.39	1.42	1.45	1.48	1.52	1.55	1.58	1.61	1.65	1.68	1.72	1.75		2.95
4% Escalation/yr thru capital project then back to 2.4%																			Supplemental LAW Feed Treated (Annual)							1		1
T&D Included plus pilot ($205M) per low end NDAA 2017 ($545M)																			Supplemental LAW Feed Treated (Cumulative)	0	0	1				83		
Estimate for key equipment replacement (melters and bubblers [NDAA 2017]) included																												
OPEX ($450M) plus relacement cost ($50M) - $500M per year																												

Note: All $450M Flat Fund alternatives will show a nominal overage of $1.7B to $2+B at start of HLW.

TSCR Basis ($15 per gallon)	$15

* Equivalent = Escalated equivalent to $450 million flat funding.

Table F-2. Example Project Cost and Funds Planning Sheet for Alternative Vitrification 1

Funding Level ($555 million/year) Consistent with Facility Completion and Operations

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	...	2075
T&D Plus Pilot Activity funded with capital project	50	75	100	125	130	75	50																					
Conceptual Planning /Approve Mission Need - CD-0	$10																											
Conceptual Design / Acquisition Strategy - CD-1		$20	$20																									
Preliminary Design / Performance Baseline - CD-2				$50	$75	$100																						
Definitive Design / Approve Start of Construction - CD-3							$150	$175																				
Procurement / Long-Lead Procurement							$125	$275	$400	$400	$250	$150	$50															
Construction									$100	$150	$200	$300	$350	$400	$400	$450	$450	$450	$300	$300	$300	$250	$50					
Startup / Cold Commissioning - CD-4																						50	$175	$225	$350			
Hot Commissioning / Operations (OPEX)																										$515		$515
FY Cost (Unescalated)	$60	$95	$120	$175	$205	$175	$325	$450	$500	$550	$450	$450	$400	$400	$400	$450	$450	$450	$300	$300	$300	$300	$225	$225	$350	$515		$515
Cum Cost (Unescalated)	$60	$155	$275	$450	$655	$830	$1,155	$1,605	$2,105	$2,655	$3,105	$3,555	$3,955	$4,355	$4,755	$5,205	$5,655	$6,105	$6,405	$6,705	$7,005	$7,305	$7,530	$7,755	$8,105	$8,620		$22,350
Escalation Factor	1.08	1.12	1.17	1.22	1.27	1.32	1.37	1.42	1.48	1.54	1.60	1.67	1.73	1.80	1.87	1.95	2.03	2.11	2.19	2.28	2.37	2.46	2.56	2.67	2.77	1.90		3.43
FY Cost (Escalated at 4%)	$65	$107	$140	$213	$259	$230	$445	$640	$740	$847	$720	$749	$693	$720	$749	$877	$912	$948	$657	$684	$711	$739	$577	$600	$970	$977		$1,768
Cum Cost (Escalated)	$65	$172	$312	$525	$784	$1,015	$1,460	$2,100	$2,840	$3,687	$4,407	$5,157	$5,849	$6,570	$7,319	$8,195	$9,107	$10,055	$10,712	$11,396	$12,107	$12,846	$13,423	$14,023	$14,993	$15,970		$51,783
Funding Level (Annual)	$579	$591	$603	$616	$629	$642	$655	$669	$683	$698	$712	$727	$742	$758	$774	$790	$807	$824	$841	$859	$877	$895	$914	$933	$953	$973		$1,635
Cumulative Funding	$579	$1,169	$1,772	$2,388	$3,017	$3,659	$4,314	$4,983	$5,667	$6,364	$7,076	$7,803	$8,546	$9,304	$10,078	$10,868	$11,675	$12,498	$13,340	$14,198	$15,075	$15,970	$16,884	$17,817	$18,770	$19,743		$51,963
Funding (Overage/Shortfall)	$514	$998	$1,460	$1,863	$2,232	$2,644	$2,855	$2,883	$2,826	$2,677	$2,669	$2,647	$2,697	$2,734	$2,759	$2,673	$2,568	$2,443	$2,627	$2,802	$2,968	$3,124	$3,461	$3,794	$3,776	$3,772		$180
																												($132)
Second LAW Vit Cost - $7.5B in FY 2023 $	Region of DFLAW plus HLW Completion and Start-Up																											
Equivalent*	$ 579	$ 591	$ 603	$ 616	$ 629	$ 642	$ 655	$ 669	$ 683	$ 698	$ 712	$ 727	$ 742	$ 758	$ 774	$ 790	$ 807	$ 824	$ 841	$ 859	$ 877	$ 895	$ 914	$ 933	$ 953	$ 973		$ 1,635
Start 2025 - spend 10% by 2032			Flat Funding		$ 555		1.18	1.21	1.23	1.26	1.28	1.31	1.34	1.37	1.39	1.42	1.45	1.48	1.52	1.55	1.58	1.61	1.65	1.68	1.72	1.75		2.95
4% Escalation/yr thru capital project then back to 2.4%																			Supplemental LAW Feed Treated (Annual)							1		1
T&D Included plus pilot ($205M) per low end NDAA 2017 ($545M)																			Supplemental LAW Feed Treated (Cumulative)	0	0	1				83		
Estimate for key equipment replacement (melters and bubblers (NDAA 2017)) included																												
OPEX ($450M) plus relacement cost ($50M) - $500M per year																												
	Note: "Viable" flat funding banks $2.8B at start of HLW.																											
TSCR Basis ($15 per gallon)	$15																											

* Equivalent = Escalated equivalent to $450 million flat funding.

Table F-3. Example Project Cost and Funds Planning Sheet for Alternative Vitrification 1 (-10%)

Reduced Capital Project Allows for Earlier Start –Funding Level ($450 million/year) is Not Consistent with Operations

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	...	2075
T&D Plus Pilot Activity funded with capital project	50	75	100	125	130	75	50																					
Conceptual Planning /Approve Mission Need - CD-0	$9																											
Conceptual Design / Acquisition Strategy - CD-1		$18	$18																									
Preliminary Design / Performance Baseline - CD-2				$45	$68	$90																						
Definitive Design / Approve Start of Construction - CD-3							$135	$158																				
Procurement / Long-Lead Procurement							$113	$248	$360	$360	$225	$135	$45															
Construction									$90	$135	$180	$270	$315	$360	$360	$405	$405	$405	$300	$300	$300	$180						
Startup / Cold Commissioning - CD-4																				45	$158	$203	$315					
Hot Commissioning / Operations (OPEX)																								$515	$530	$545		$515
FY Cost (Unescalated)	$59	$93	$118	$170	$198	$165	$298	$405	$450	$495	$405	$405	$360	$360	$360	$405	$405	$405	$300	$345	$458	$383	$315	$515	$530	$545		$515
Cum Cost (Unescalated)	$59	$152	$270	$440	$638	$803	$1,100	$1,505	$1,955	$2,450	$2,855	$3,260	$3,620	$3,980	$4,340	$4,745	$5,150	$5,555	$5,855	$6,200	$6,658	$7,040	$7,355	$7,870	$8,400	$8,945		$22,600
Escalation Factor	1.08	1.12	1.17	1.22	1.27	1.32	1.37	1.42	1.48	1.54	1.60	1.67	1.73	1.80	1.87	1.95	2.03	2.11	2.19	2.28	2.37	2.46	2.56	1.81	1.86	1.90		3.43
FY Cost (Escalated @ 4%)	$64	$105	$138	$207	$250	$217	$407	$576	$666	$762	$648	$674	$623	$648	$674	$789	$820	$853	$657	$786	$1,084	$943	$807	$932	$986	$1,034		$1,768
Cum Cost (Escalated)	$64	$168	$306	$513	$763	$980	$1,387	$1,964	$2,630	$3,392	$4,040	$4,715	$5,338	$5,987	$6,661	$7,450	$8,270	$9,123	$9,781	$10,567	$11,651	$12,594	$13,401	$14,334	$15,319	$16,353		$51,892
Funding Level (Annual)	$469	$479	$489	$499	$510	$520	$531	$543	$554	$566	$577	$590	$602	$615	$628	$641	$654	$668	$682	$696	$711	$726	$741	$757	$772	$789		$1,326
Cumulative Funding	$469	$948	$1,437	$1,936	$2,446	$2,967	$3,498	$4,041	$4,594	$5,160	$5,738	$6,327	$6,929	$7,544	$8,171	$8,812	$9,466	$10,134	$10,816	$11,512	$12,223	$12,949	$13,690	$14,446	$15,219	$16,007		$42,132
Funding (Overage/Shortfall)	$405	$780	$1,131	$1,423	$1,683	$1,986	$2,110	$2,077	$1,964	$1,768	$1,697	$1,612	$1,591	$1,557	$1,510	$1,362	$1,196	$1,010	$1,035	$945	$572	$355	$288	$113	($101)	($346)		($9,760)
																												($442)
Second LAW Vit Cost - $7.5B in FY 2023 $	Region of DFLAW plus HLW Completion and Start-Up																											
Equivalent*	$ 469	$ 479	$ 489	$ 499	$ 510	$ 520	$ 531	$ 543	$ 554	$ 566	$ 577	$ 590	$ 602	$ 615	$ 628	$ 641	$ 654	$ 668	$ 682	$ 696	$ 711	$ 726	$ 741	$ 757	$ 772	$ 789		$ 1,326
Start 2025 - spend 10% by 2032		Flat Funding			$ 450		1.18	1.21	1.23	1.26	1.28	1.31	1.34	1.37	1.39	1.42	1.45	1.48	1.52	1.55	1.58	1.61	1.65	1.68	1.72	1.75		2.95
4% Escalation/yr thru capital project then back to 2.4%																												
T&D Included plus pilot ($205M) per low end NDAA 2017 ($545M)																												
Estimate for key equipment replacement (melters and bubblers (NDAA 2017)) included																												
OPEX ($450M) plus relacement cost ($50M) - $500M per year																												
TSCR Basis ($15 per gallon)	$15																											

Supplemental LAW Feed Treated (Annual) 1 2 3 1

Supplemental LAW Feed Treated (Cumulative) 1 3 6 83

Note: All $450M Flat Fund alternatives will show a nominal overage of $1.7B to $2+B at start of HLW.

* Equivalent = Escalated equivalent to $450 million flat funding.

Table F-4. Alternative Vitrification 1: Summary of Results for Base Case and Sensitivities

Vitrification 1	CD-4	Supplemental LAW Mission Complete	Flat Funding $M	Flat Funding with Operations $M	Final Cost (escalated) $M
Base	2050	2075	$ 450	$ 555	$ 51,783
Base -10%	2048	2074	$ 450	$ 550	$ 51,083
Base +100%	2068	2088	$ 645	$ 645	$ 88,359
Base with 8% escalation	2056	2075	$ 900	$ 900	$ 71,323

CD = critical decision.
LAW = low-activity waste.

Table F-5. Example Project Cost and Funds Planning Sheet for Alternative FBSR 1A

FBSR Base Example (4% Escalation Applied to CAPEX) and $450 Million/Year Basis

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	…	2070
T&D Plus Pilot Activity funded with capital project	50	75	100	125	130	75	50																					
Conceptual Planning /Approve Mission Need - CD-0				$10																								
Conceptual Design / Acquisition Strategy - CD-1		$5			$30				On-site FBSR																			
Preliminary Design / Performance Baseline - CD-2			$10			$50	$75																					
Definitive Design / Approve Start of Construction - CD-3			$10	$20			$100	$150																				
Procurement / Long-Lead Procurement				$56	$36			$100	$125	$175																		
Construction		Evaporator		$40	80	$45				$200	$450	$450	$325															
Startup / Cold Commissioning - CD-4					$5	$20	$21						$50	$100	$180													
Hot Commissioning / Operations (OPEX)																131	146	161	168.5	176	176	176	176	161	161	161		131
FY Cost (Unescalated)	$50	$80	$120	$251	$281	$190	$246	$250	$125	$375	$450	$450	$375	$100	$180	$131	$146	$161	$169	$176	$176	$176	$176	$161	$161	$161		$131
Cum Cost (Unescalated)	$50	$130	$250	$501	$782	$972	$1,218	$1,468	$1,593	$1,968	$2,418	$2,868	$3,243	$3,343	$3,523	$3,654	$3,800	$3,961	$4,130	$4,306	$4,482	$4,658	$4,834	$4,995	$5,156	$5,317		$8,417
Escalation Factor	1.08	1.12	1.17	1.22	1.27	1.32	1.37	1.42	1.48	1.54	1.60	1.67	1.73	1.80	1.87	1.50	1.53	1.57	1.61	1.65	1.68	1.73	1.77	1.81	1.85	1.90		3.05
FY Cost (Escalated at 4%)	$54	$90	$140	$305	$356	$250	$337	$356	$185	$577	$720	$749	$649	$180	$337	$196	$224	$253	$271	$290	$297	$304	$311	$291	$298	$305		$399
Cum Cost (Escalated)	$54	$144	$284	$590	$945	$1,195	$1,532	$1,888	$2,073	$2,650	$3,371	$4,120	$4,769	$4,949	$5,287	$5,483	$5,706	$5,959	$6,230	$6,519	$6,816	$7,120	$7,431	$7,722	$8,020	$8,326		$15,886
Funding Level (Annual)	$469	$479	$489	$499	$510	$520	$531	$543	$554	$566	$577	$590	$602	$615	$628	$641	$654	$668	$682	$696	$711	$726	$741	$757	$772	$789		$1,195
Cumulative Funding	$469	$948	$1,437	$1,936	$2,446	$2,967	$3,498	$4,041	$4,594	$5,160	$5,738	$6,327	$6,929	$7,544	$8,171	$8,812	$9,466	$10,134	$10,816	$11,512	$12,223	$12,949	$13,690	$14,446	$15,219	$16,007		$35,769
Funding (Overage/Shortfall)	$415	$804	$1,153	$1,347	$1,501	$1,771	$1,966	$2,153	$2,522	$2,510	$2,367	$2,207	$2,160	$2,594	$2,885	$3,329	$3,760	$4,175	$4,586	$4,993	$5,407	$5,829	$6,259	$6,724	$7,199	$7,682		$19,883
Second LAW Vit Cost - $FBSR in FY 2023 $	Region of DFLAW plus HLW Completion and Start-Up																											
Funding Limit $450M/Yr																												
Start 2025 - capture development cost	**450** Flat Funding			1.021																								
4% Escalation/yr thru 2039 then 2.4%																												
														gal		1	2	3	3.5	4	4	4	4	3	3	3		1
Assumes off-site capital estimate ($2570M) from NDAA 2017 with low end T&D estimate plus $225M pilot - total $605 M (unescalated)														cum gal	0	1	3	6	9.5	13.5	17.5	21.5	25.5	28.5	31.5	34.5		86.5
Cost per TSCR Gallon	15																											

Table F-6. Example Project Cost and Funds Planning Sheet for Alternative FBSR 1A

FBSR Sensitivity with 8% Escalation Applied to CAPEX

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	…	2070
T&D Plus Pilot Activity funded with capital project	50	75	100	125	130	75	50																					
Conceptual Planning /Approve Mission Need - CD-0				$10																								
Conceptual Design / Acquisition Strategy - CD-1		$5			$30				On-site FBSR																			
Preliminary Design / Performance Baseline - CD-2			$10			$50	$75																					
Definitive Design / Approve Start of Construction - CD-3			$10	$20			$100	$150																				
Procurement / Long-Lead Procurement				$56	$36			$100	$125	$175																		
Construction		Evaporator		$40	80	$45				$200	$450	$450	$325															
Startup / Cold Commissioning - CD-4					$5	$20	$21						$50	$100	$180													
Hot Commissioning / Operations (OPEX)																131	146	161	168.5	176	176	176	176	161	161	161		131
FY Cost (Unescalated)	$50	$80	$120	$251	$281	$190	$246	$250	$125	$375	$450	$450	$375	$100	$180	$131	$146	$161	$169	$176	$176	$176	$176	$161	$161	$161		$131
Cum Cost (Unescalated)	$50	$130	$250	$501	$782	$972	$1,218	$1,468	$1,593	$1,968	$2,418	$2,868	$3,243	$3,343	$3,523	$3,654	$3,800	$3,961	$4,130	$4,306	$4,482	$4,658	$4,834	$4,995	$5,156	$5,317		$8,417
Escalation Factor	1.17	1.26	1.36	1.47	1.59	1.71	1.85	2.00	2.16	2.33	2.52	2.72	2.94	3.17	3.43	1.50	1.53	1.57	1.61	1.65	1.68	1.73	1.77	1.81	1.85	1.90		3.05
FY Cost (Escalated at 8%)	$58	$101	$163	$369	$446	$326	$455	$500	$270	$874	$1,133	$1,224	$1,101	$317	$617	$196	$224	$253	$271	$290	$297	$304	$311	$291	$298	$305		$399
Cum Cost (Escalated)	$58	$159	$322	$691	$1,137	$1,463	$1,918	$2,418	$2,688	$3,562	$4,695	$5,919	$7,020	$7,338	$7,954	$8,150	$8,374	$8,627	$8,898	$9,187	$9,484	$9,787	$10,098	$10,390	$10,688	$10,993		$18,553
Funding Level (Annual)	$469	$479	$489	$499	$510	$520	$531	$543	$554	$566	$577	$590	$602	$615	$628	$641	$654	$668	$682	$696	$711	$726	$741	$757	$772	$789		$1,195
Cumulative Funding	$469	$948	$1,437	$1,936	$2,446	$2,967	$3,498	$4,041	$4,594	$5,160	$5,738	$6,327	$6,929	$7,544	$8,171	$8,812	$9,466	$10,134	$10,816	$11,512	$12,223	$12,949	$13,690	$14,446	$15,219	$16,007		$35,769
Funding (Overage/Shortfall)	$411	$789	$1,115	$1,245	$1,309	$1,504	$1,580	$1,623	$1,907	$1,598	$1,042	$408	($91)	$206	$217	$661	$1,092	$1,507	$1,918	$2,325	$2,739	$3,161	$3,591	$4,057	$4,531	$5,014		$17,216
Second LAW Vit Cost - $FBSR in FY 2023 $	Region of DFLAW plus HLW Completion and Start-Up																											
Start 2025 - capture development cost	**450** Flat Funding			1.021																								
8% Escalation/yr thru 2039 then 2.4%																												
														gal	0	1	2	3	3.5	4	4	4	4	3	3	3		1
Assumes offsite capital estimate ($2570M) from NDAA 2017 with low end T&D estimate plus $225M pilot - total $605 M (unescalated)														cum gal	0	1	3	6	9.5	13.5	17.5	21.5	25.5	28.5	31.5	34.5		86.5
Cost per TSCR Gallon	15																											

Table F-7. Example Project Cost and Funds Planning Sheet for Alternative Grout 1A

Sensitivity Case with 8% Escalation Applied to Grout CAPEX

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	…	2068
T&D Plus Pilot Activity funded with capital project	15	20	25	25	20	10	5																					
Conceptual Planning /Approve Mission Need - CD-0			$10																									
Conceptual Design / Acquisition Strategy - CD-1	$5			$30																								
Preliminary Design / Performance Baseline - CD-2		$10			$50	$75		East Plant																				
Definitive Design / Approve Start of Construction - CD-3		$10	$20			$15	$30																					
Procurement / Long-Lead Procurement			$56	$36		$40	$80	$40																				
Construction			$40	80	$45		$40	100	$100	$40																		
Startup / Cold Commissioning - CD-4		Evaporator		$5	$20	$21			$20	$25	$35																	
Hot Commissioning / Operations (OPEX)											75	90	105	112.5	120	105	105	105	105	105	105	105	105	105	105	105		75
FY Cost (Unescalated)	$20	$40	$151	$176	$135	$161	$155	$140	$120	$65	$110	$90	$105	$113	$120	$105	$105	$105	$105	$105	$105	$105	$105	$105	$105	$105		$75
Cum Cost (Unescalated)	$20	$60	$211	$387	$522	$683	$838	$978	$1,098	$1,163	$1,273	$1,363	$1,468	$1,581	$1,701	$1,806	$1,911	$2,016	$2,121	$2,226	$2,331	$2,436	$2,541	$2,646	$2,751	$2,856		$4,611
Escalation Factor	1.17	1.26	1.36	1.47	1.59	1.71	1.85	2.00	2.16	2.33	2.52	1.36	1.39	1.43	1.46	1.50	1.53	1.57	1.61	1.65	1.68	1.73	1.77	1.81	1.85	1.90		2.91
FY Cost (Escalated at 8%)	$23	$50	$205	$259	$214	$276	$287	$280	$259	$152	$277	$123	$146	$161	$175	$157	$161	$165	$169	$173	$177	$181	$186	$190	$195	$199		$218
Cum Cost (Escalated)	$23	$74	$279	$538	$752	$1,028	$1,315	$1,595	$1,854	$2,005	$2,282	$2,405	$2,551	$2,712	$2,887	$3,044	$3,205	$3,370	$3,539	$3,711	$3,888	$4,070	$4,255	$4,445	$4,640	$4,839		$8,994
Funding Level (Annual)	$469	$479	$489	$499	$510	$520	$531	$543	$554	$566	$577	$590	$602	$615	$628	$641	$654	$668	$682	$696	$711	$726	$741	$757	$772	$789		$200
Cumulative Funding	$469	$948	$1,437	$1,936	$2,446	$2,967	$3,498	$4,041	$4,594	$5,160	$5,738	$6,327	$6,929	$7,544	$8,171	$8,812	$9,466	$10,134	$10,816	$11,512	$12,223	$12,949	$13,690	$14,446	$15,219	$16,007		$31,534
Funding (Overage/Shortfall)	$446	$874	$1,158	$1,399	$1,694	$1,939	$2,183	$2,446	$2,741	$3,155	$3,455	$3,922	$4,378	$4,832	$5,284	$5,768	$6,261	$6,764	$7,277	$7,801	$8,335	$8,879	$9,435	$10,001	$10,579	$11,169		$22,539
	Region of DFLAW plus HLW Completion and Start-Up																											
Funding Limit $450M/Yr																												
Start 2025 - capture development cost	Flat Funding								gal		1	2	3	3.5	4	3	3	3	3	3	3	3	3	3	3	3		1
8% Escalation/yr thru 2035 then 2.4% for OPEX	$ 450	1.021							T gal		1	3	6	9.5	13.5	16.5	19.5	22.5	25.5	28.5	31.5	34.5	37.5	40.5	43.5	46.5		91.5
Basis rounded to $60 per gallon																												
Evap Op's set at $15M per year	NA																											
TSCR Op's Set at $15 to $52.5		15																										

Table F-8. Example Project Cost and Funds Planning Sheet for Alternative Grout 4B

No On-site Grout Facility Required, so Any Sensitivity would be Based on Off-site Grouting and Disposal Cost

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	…	2065
T&D funded separate - no grout plant	15	20	25	25	20	10	5																					
Conceptual Planning /Approve Mission Need - CD-0																												
Conceptual Design / Acquisition Strategy - CD-1																												
Preliminary Design / Performance Baseline - CD-2																												
Definitive Design / Approve Start of Construction - CD-3	$26																											
Procurement / Long-Lead Procurement	$56	$36																										
Construction	$40	80	$45																									
Startup / Cold Commissioning - CD-4		$5	$20	$21																								
Hot Commissioning / Operations (OPEX)			60	120	120	120	150	150	150	180	180	180	210	210	210	210	180	180	180	180	180	180	180	180	180	180		60
FY Cost (Unescalated)	$137	$141	$150	$166	$140	$130	$155	$150	$150	$180	$180	$180	$210	$210	$210	$210	$180	$180	$180	$180	$180	$180	$180	$180	$180	$180		$60
Cum Cost (Unescalated)	$137	$278	$428	$594	$734	$864	$1,019	$1,169	$1,319	$1,499	$1,679	$1,859	$2,069	$2,279	$2,489	$2,699	$2,879	$3,059	$3,239	$3,419	$3,599	$3,779	$3,959	$4,139	$4,319	$4,499		$6,449
Escalation Factor	1.05	1.07	1.10	1.13	1.15	1.18	1.21	1.24	1.27	1.30	1.33	1.36	1.39	1.43	1.46	1.50	1.53	1.57	1.61	1.65	1.68	1.73	1.77	1.81	1.85	1.90		2.71
FY Cost (Escalated at 2.4%)	$144	$151	$165	$187	$161	$153	$187	$186	$190	$234	$239	$245	$293	$300	$307	$314	$276	$282	$289	$296	$303	$311	$318	$326	$333	$341		$162
Cum Cost (Escalated)	$144	$295	$460	$647	$808	$962	$1,149	$1,335	$1,525	$1,759	$1,998	$2,243	$2,536	$2,835	$3,142	$3,457	$3,732	$4,015	$4,304	$4,600	$4,904	$5,214	$5,532	$5,858	$6,191	$6,533		$10,950
Funding Level (Annual)	$469	$479	$489	$499	$510	$520	$531	$543	$554	$566	$577	$590	$602	$615	$628	$641	$654	$668	$682	$696	$711	$726	$741	$757	$772	$789		$1,077
Cumulative Funding	$469	$948	$1,437	$1,936	$2,446	$2,967	$3,498	$4,041	$4,594	$5,160	$5,738	$6,327	$6,929	$7,544	$8,171	$8,812	$9,466	$10,134	$10,816	$11,512	$12,223	$12,949	$13,690	$14,446	$15,219	$16,007		$30,034
Funding (Overage/Shortfall)	$325	$653	$977	$1,289	$1,638	$2,005	$2,349	$2,706	$3,069	$3,401	$3,740	$4,084	$4,393	$4,708	$5,029	$5,355	$5,734	$6,119	$6,512	$6,912	$7,319	$7,735	$8,158	$8,588	$9,027	$9,475		$19,084
Second LAW Offsite Grout - $330 Evap in FY 2023 $	Region of DFLAW plus HLW Completion and Start-Up																											
Funding Limit $450M/Yr																												
Start 2025 - Early evap costs carried into 2025 CD-3	450	Flat Funding		1.021																								
2.4% Escalation/yr																												
Grouting at $30 / Gallon 2023																												
100M Gallon Basis																												
gal		1	2	2	2	2.5	2.5	2.5	3	3	3	3.5	3.5	3.5	3.5	3	3	3	3	3	3	3	3	3	3	3		1
Basis rounded to $45 per gallon (Sandia analysis this study) T gal		1	3	5	7	9.5	12	14.5	17.5	20.5	23.5	27	30.5	34	37.5	40.5	43.5	46.5	49.5	52.5	55.5	58.5	61.5	64.5	67.5		100
Evap Op's set at $15M per year	15																											
TSCR Op's Set at $15 per gallon	15																											

Table F-9. Example Project Cost and Funds Planning Sheet for Alternative Grout 6

Sensitivity Case with 8% Escalation Applied to Grouting Facility

		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	…	2065
T&D funded separate - no grout plant		15	20	25	25	20	10	5																					
Conceptual Planning /Approve Mission Need - CD-0																													
Conceptual Design / Acquisition Strategy - CD-1																													
Preliminary Design / Performance Baseline - CD-2									On-site Grout (See Below)																				
Definitive Design / Approve Start of Construction - CD-3		$26																											
Procurement / Long-Lead Procurement		$56	$36																										
Construction		$40	80	$45																									
Startup / Cold Commissioning - CD-4			$5	$20	$21																								
Hot Commissioning / Operations (OPEX)				60	120	120	120	150	150	150	180	180	180	210	210	210	112.5	105	105	105	105	105	105	105	105	105	105		75
FY Cost (Unescalated)		$137	$141	$150	$166	$140	$130	$155	$150	$150	$180	$180	$180	$210	$210	$210	$113	$105	$105	$105	$105	$105	$105	$105	$105	$105	$105		$75
Cum Cost (Unescalated)		$137	$278	$428	$594	$734	$864	$1,019	$1,169	$1,319	$1,499	$1,679	$1,859	$2,069	$2,279	$2,489	$2,602	$2,707	$2,812	$2,917	$3,022	$3,127	$3,232	$3,337	$3,442	$3,547	$3,652		$5,039
Escalation Factor		1.05	1.07	1.10	1.13	1.15	1.18	1.21	1.24	1.27	1.30	1.33	1.36	1.39	1.43	1.46	1.50	1.53	1.57	1.61	1.65	1.68	1.73	1.77	1.81	1.85	1.90		2.71
FY Cost (Escalated at 2.4% OPEX)		$144	$151	$165	$187	$161	$153	$200	$227	$264	$442	$499	$507	$535	$442	$389	$168	$161	$165	$169	$173	$177	$181	$186	$190	$195	$199		$203
Cum Cost (Escalated)		$144	$295	$460	$653	$832	$1,003	$1,243	$1,551	$1,924	$2,597	$3,372	$4,157	$4,943	$5,550	$6,059	$6,292	$6,527	$6,763	$7,014	$7,262	$7,472	$7,688	$7,931	$8,174	$8,447	$8,714		$11,995
Funding Level (Annual)		$469	$479	$489	$499	$510	$520	$531	$543	$554	$566	$577	$590	$602	$615	$628	$641	$654	$668	$682	$696	$711	$726	$741	$757	$772	$789		$1,077
Cumulative Funding		$469	$948	$1,437	$1,936	$2,446	$2,967	$3,498	$4,041	$4,594	$5,160	$5,738	$6,327	$6,929	$7,544	$8,171	$8,812	$9,466	$10,134	$10,816	$11,512	$12,223	$12,949	$13,690	$14,446	$15,219	$16,007		$30,034
Funding (Overage/Shortfall)		$325	$653	$977	$1,284	$1,614	$1,964	$2,255	$2,490	$2,670	$2,563	$2,366	$2,170	$1,986	$1,993	$2,112	$2,520	$2,939	$3,371	$3,802	$4,250	$4,751	$5,261	$5,758	$6,272	$6,772	$7,294		$18,039
Second LAW Offsite Grout - $330 Evap in FY 2023 $		Region of DFLAW plus HLW Completion and Start-Up																											
Funding Limit $450M/Yr																													
Start 2025 - with carry spent into CD-3		450	Flat Funding			1.021																							
2.4% Escalation/yr (OPEX)																													
Grouting at $45 / Gallon 2023																													
100M Gallon Basis																													
$10M for WFE (TSCR West added to 2027 OPEX)	gal			1	2	2	2	2.5	2.5	2.5	3	3	3	3.5	3.5	3.5	3.5	3	3	3	3	3	3	3	3	3	3		1
Basis rounded to $60 per gallon	T gal			1	3	5	7	9.5	12	14.5	17.5	20.5	23.5	27	30.5	34	37.5	40.5	43.5	46.5	49.5	52.5	55.5	58.5	61.5	64.5	67.5		100
Evap Op's set at $15M per year		15																											
TSCR Op's Set at $15 to $52.5		15																											
GDU Construction																													
CD-0			$5						GDU																				
CD-1				$10																									
CD-2			$ 5	$ 10										$ 5	$ 10														
CD-3				$ 4	$ 12										$ 4	12				GDU				$ 5	$ 10				GDU
Long Lead Procurement					$ 9	$ 10										9	10								$ 4	12	10		
Construction						$ 20	$ 25	$ 10									20	25	10							9	20	25	
Start-Up							$ 5	$ 10	10										5	10	10								
Conceptual Planning /Approve Mission Need - CD-0						$10																							
Conceptual Design / Acquisition Strategy - CD-1							$30																						
Preliminary Design / Performance Baseline - CD-2								$50	$75				On-site Grout				$ 5	$ 10											
Definitive Design / Approve Start of Construction - CD-3									$15	$30							$ 4	12				GDU							
Procurement / Long-Lead Procurement									$40	$80	$40							9	10										
Construction										$40	100	$100	$40						20	25	10								
Startup / Cold Commissioning - CD-4												$20	$25	$35							5	10	10						
Escalation based on 2.4% 'till **Grout Plant** Start	Esc Factor						1.18	1.27	1.38	1.49	1.61	1.73	1.87	2.02	2.18	2.36													
Escalation at 8% thru CD-4 last GDU																													
	Cost -Unescalated							$10	$30	$50	$130	$150	$140	$120	$65	$35													
								$10	$40	$90	$220	$370	$510	$630	$695	$730													
	Cost Escalated							$13	$41	$74	$209	$260	$262	$243	$142	$83													
Top + Grout P + GDU Cumulative Cost (Unescalated)		$137	$278	$428	$599	$749	$878	$1,050	$1,239	$1,434	$1,734	$2,059	$2,379	$2,704	$2,988	$3,240	$2,637	$2,746	$2,848	$2,957	$3,057	$3,142	$3,247	$3,361	$3,463	$3,577	$3,677		$5,039
Escalation based on 2.4% 'till GDU 1 Start				1.10	1.14	1.19	1.24	1.29	1.34	1.39	1.45	1.50	1.56	1.63	1.69	1.76	1.83	1.90	1.98	2.06	2.14	2.23	2.32	2.41	2.51	2.61	2.71		
Escalation at 4% thru CD-4 GDU 4 (2053)																													
	Cost -Unescalated				$ 5	$ 15	$ 14	$ 21	$ 30	$ 25	$ 15	$ 10	$ 10	$ 5	$ 14	$ 21	$ 35	$ 39	$ 36	$ 40	$ 35	$ 15	$ 15	$ 24	$ 21	$ 30	$ 25		
					$ 5	$ 20	$ 34	$ 55	$ 85	$ 110	$ 125	$ 135	$ 145	$ 150	$ 164	$ 185	$ 220	$ 259	$ 295	$ 335	$ 370	$ 385	$ 400	$ 424	$ 445	$ 475	$ 500		
	Cost Escalated				$ 6	$ 18	$ 17	$ 27	$ 40	$ 35	$ 22	$ 15	$ 16	$ 8	$ 24	$ 37	$ 64	$ 74	$ 71	$ 82	$ 75	$ 33	$ 35	$ 58	$ 53	$ 78	$ 68		

F.2.2.1 Alternative Vitrification 1

Table F-1 through Table F-4 **(Vitrification 1)** reflect the development and construction of a facility (with nominally 3× the throughput of the LAW Vitrification Facility) with startup complete no earlier than 2047. This project has an extended schedule consistent with large, unique nuclear facilities. Process operations include the point estimates for annual operations ($450 million/year – about 40% higher than projected for the WTP LAW Vitrification Facility) and essential equipment ($50 million, predominately replacement melters and bubblers) from the NDAA17 study (SRNL-RP-2018-00687). Pretreatment costs via tank-side cesium removal (TSCR) are apportioned to LAW supplemental treatment at $15/gal and matched to the gallonage projected per year.

As described earlier, flat funding for the vitrification project is in excess of the $450 million target for all sensitivities. Note that the near-term cost (from the start of DFLAW through HLW vitrification startup), cumulative cost is in excess of $4.0 billion.[9]

F.2.2.2 Alternative FBSR 1A

Table F-5 (FBSR 1A) reflects the development and construction of a facility (nominally 2.5× throughput of LAW vitrification) with startup complete in 2039. This project has an extended schedule consistent with large, unique nuclear facilities. Process operations include point estimates for operations ($90 million/year) and essential equipment ($26 million/year) from the NDAA17 study (SRNL-RP-2018-00687).[10] This is significantly lower than for vitrification. Pretreatment costs via TSCR are apportioned to LAW supplemental treatment at $15/gal.[11],[12] Operational costs for FBSR alternatives appear to be significantly lower than for vitrification.

Table F-6 shows that one sensitivity case for FBSR 1A could not be executed within the benchmark budget. If capital project escalation were to be 8% instead of the assumed base level of 4%, an average annual funding level of ≈$720 million would be needed to complete the mission, with operations commencing in ~2046. Since the funding bottleneck in this case is construction and not operations, the capital project schedule could instead be increased to allow completion at lower annual funding levels, but only at the expense of a longer overall treatment mission (as per Figure F-2). For the period through HLW vitrification startup, cumulative cost would exceed $2.1 billion.

[9] No primary cost elements were common between WRPS Mission Integration Analysis – per the lifecycle cost model for Vitrification 1 (modified), also referred to as the Analysis of Alternatives (AoA) Scenario 18 Phased Startup – and this analysis. This analysis used a $7.5 billion point estimate for the capital project with allocated funding as per the timeline shown in Figure F-2. The annual OPEX basis (2048 through 2075) was $450 million (per the NDAA17 study), reflecting a 1.4 factor set against the most recent projection for WTP LAW Vitrification Facility versus a 1.6 factor (with OPEX running 2050 through 2075). This analysis provides an unescalated, constant dollar projection for the vitrification facility (CAPEX plus OPEX) of $23.4 billion versus $24.1 billion generated by the lifecycle cost model for the TOPSim Vitrification 1 (modified) scenario.

[10] There is considerably less operational history for FBSR within the DOE complex than for the other treatment options considered. As such, the uncertainty in design/construction, operations and equipment replacement was viewed as higher. The NDAA17 estimate for off-site FBSR (with large load-out facility) was used for both FBSR (onsite and offsite) cost and funding spreadsheets. The operations estimate was taken from the lower range (FBSR Case 1 – NDAA17) and matched with high-end equipment replacement (FBSR Case 2 – NDAA17).

[11] For reference, off-site transportation and disposal costs (for FBSR 1B) were calculated for this study and estimated at $20/gal feed (Volume II, Appendix H).

[12] FBSR has a greater volume reduction factor than grout, which reduced transportation costs, but a greater fraction of the waste was determined to be Class B versus grout.

F.2.2.3 Alternative Grout 1A

Table F-7 (Grout 1A) reflects the development and construction of an on-site grout facility with operations starting in 2035.[13] Process operations and equipment placement point estimates from the NDAA17 report (Offsite Grout) were considered consistent with the containerized grout facility. Grout 1A is provided as an example for review as it is the least expensive option. All sensitivities, including 8% escalation (as shown) of the grout facility project are well within the $450 million flat funding benchmark. For the period through HLW vitrification startup, the cumulative cost is ≈$1.2 billion.

F.2.2.4 Alternative Grout 4B

Table F-8 (Grout 4B) reflects the construction and startup of an evaporator for processing LAW feed and off-site disposition costs for grouting, transportation, and disposal, with off-site operations commencing in 2027 (200 West Area TSCR) and 2028 (200 East Area TSCR and tank farms pretreatment [TFPT] excess). Process operations are based on $30 or $45/gal (unescalated) for grouting and an additional $15 for transportation and disposal.[14] Pretreatment costs via TSCR are apportioned to LAW supplemental treatment at $15/gal and matched to the gallonage projected per year.

Table F-8 shows that for the period through HLW vitrification startup, cumulative cost is just over $1.2 billion. This includes the cost of 14 Mgal of LAW feed dispositioned.[15]

F.2.2.5 Alternative Grout 6

Alternative Grout 6 is a hybrid of Alternatives Grout 4B and 5A. Table F-9 reflects the construction and startup of an evaporator and early off-site disposition costs as per Grout 4B, along with the construction of a grout plant and grout disposal units (GDU) (four) with the on-site grout mission initiating in 2040. Process operations are based on $30 or $45/gal grouting (unescalated), with an additional $15/gal for transportation and disposal. Pretreatment costs via TSCR are apportioned to LAW supplemental treatment at $15/gal and matched to the gallonage projected per year. For the period through HLW vitrification startup, Grout 6 shows a cumulative cost of $1.5 billion, which includes the cost of 14 Mgal of LAW feed dispositioned.

F.2.2.6 Comparative Costs

Comparative costs (both unescalated and constant year) for all process alternatives are provided in Table F-10 (on the next page). Several general observations can be made.

1. Vitrification for LAW supplemental treatment, as analyzed by this study, is the highest cost alternative and is shown to provide for the longest duration tank waste processing mission. A project to construct a facility for a late 2040s to 2050 start-up date is not consistent with project goals of limiting funding near-term – to avoid impacting DFLAW processing or HLW vitrification startup. Likewise, if the current WTP LAW Vitrification Facility is used as an analog, facility operations will cost several times that of any other alternative.

[13] Grout process diagrams, such as those found in Volume II, Appendix C often reflect an oxidation operation if excess organics are detected in the incoming feed. This operation is not costed herein as the LAW Vitrification Facility is assumed in service and could be used to treat that volume.

[14] Costs shown in Table F-9 reflect the higher ($45/gal) cost for grouting. A lower cost estimate, based on the Energy*Solutions*, Clive Disposal Facility price list rounded to $30/gal, was also evaluated. This quote was used to determine a lower range cost for off-site grout disposition and is captured in Table F-10.

[15] No primary cost elements were shared between WRPS system planning – the lifecycle cost model for Grout 4B – and this analysis. System planning provided a detailed estimate of off-site pretreatment and disposal costs ($75/gal), 200 East/West Area TSCR operations, TSCR costs, load-out stations, and related activities. For the time period through HLW startup, LAW supplemental treatment increased cost to $1.6 billion (unescalated), or $2 billion (escalated). For the same period, this analysis determined a cost differential of $1.5 billion (unescalated, assuming $45/gal for grout).

2. FBSR, as analyzed by this study, is intermediate between vitrification and all grout alternatives regarding projected schedule and cost. Facility operations costs appear more in line with grouting, assuming an on-site disposition option; the projected Class A/B split impacts off-site disposition option for FBSR significantly.
3. Grouting processes, as analyzed by this study, are the lowest cost alternatives and appear to be consistent with limiting near-term funding and providing support for minimizing the tank waste processing mission. All alternatives are consistent with the benchmark budget of $450 million/year.

Table F-10. Calculated Cost of Low-Activity Waste Supplemental Alternatives

Alternative	Project cost		Total ($M)
	CAPEX ($M)	OPEX ($M)	
Vitrification 1	11,809	15,434	27,243
FBSR 1A	4,690	5,237	9,927
FBSR 1B	4,712	7,032	11,744
Grout 1A	1,443	3,576	5,019
Grout 1B	1,459	5,056	6,515
Grout 1C	1,572	4,222	5,794
Grout 2A	2,006	4,131	6,137
Grout 2B	2,037	6,134	8,171
Grout 2C	2,136	4,953	7,089
Grout 4A	422	5,477	5,899
Grout 4B	431	6,429	6,860
Grout 5A	1,710	4,364	6,074
Grout 6	978	5,891	6,869

CAPEX = capital expenditure. OPEX = operations expenditure.
FBSR = fluidized bed steam reforming.

F.2.3 Converging Low-Activity Waste Supplemental Treatment and Tank Waste Mission Analyses

The above analysis was performed to provide comparisons between LAW supplemental treatment alternatives. Previous work based on unit operations, and the chemical modeling and associated lifecycle cost modeling tools used for DOE Office of River Protection (ORP), identified the impact/need for LAW supplemental treatment – as per the TC&WM EIS (DOE/EIS-0391) and impacts to mission completion schedule if delayed. One 2021 study provided an analysis for a mission combining a cost-unconstrained vitrification facility project with LAW supplemental treatment delayed until 2050. This is within the range (early side) shown in Figure F-1 and Figure F-2. This model run (simulations supporting ORP are performed by the TOPSim model), MR-50638, was used to provide a parallel analysis for LAW supplemental treatment based on unconstrained project cost and a fixed-date schedule.

This model run, referred to hereafter as Vitrification 1 (modified), was performed by the WRPS Mission Integration Analysis organization and provides a holistic mission view (e.g., LAW/HLW vitrification and tank retrievals) view consistent with analyses, such as those reported in the ORP System Plans (ORP-11242).[16]

Building on this adaption to methodology, a grout alternative (Grout 4B) was independently evaluated using the same system planning tools to provide linkage to those system planning bases and improve comparisons.[17] The inclusion of the system planning tool modeling connects the process logic developed for this study to the Hanford Site mission capability (current and projected). The system planning (and lifecycle cost model) effort regarding the grout alternative (Grout 4B) allows for direct comparison with the Vitrification 1 (modified) run results. Comparisons between the Grout 4B scenario, as developed for this study, with the Vitrification 1 (modified) run can be made to illustrate both mission and LAW supplemental treatment specific costs. Finally, interpolating the mission results between the grout and vitrification options as modeled by system planning tools allows for additional comparisons of the various LAW supplemental treatment alternatives specific to this study.

An overview of the computational tools used to support ORP in projecting the clean-up mission for project performance and cost is provided in Figure F-3. The key tool is the TOPSim computational software, a process modeling platform purpose built to support mission planning.

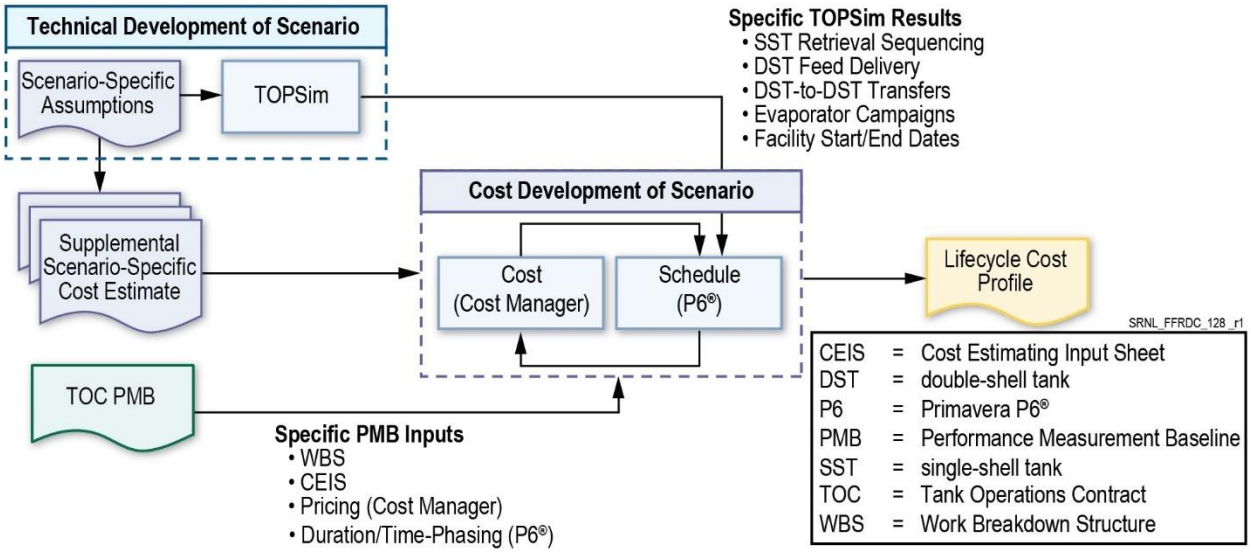


Figure F-3. Overview of the Mission Modeling and Cost Estimating Software used for DOE Office of River Protection System Planning

The logic behind each scenario is converted into TOPSim input as specific assumptions regarding facility start-up dates and performance in conjunction with tank farm conditions and infrastructure availability, among others. The time-stamped mission results generated by TOPSim are then reflected as a performance schedule, and the cost elements are applied to provide a lifecycle cost profile. This profile is provided in both unescalated constant dollars and with 2.4% annual escalation (from the start of the scenario) applied.[18]

[16] This scenario, Vitrification 1 (modified), does provide for off-site grout specific to support SST retrievals in the 200 West Area, but is centered on a large LAW supplemental treatment vitrification facility near the current WTP.

[17] Note that the costs presented as unescalated dollars are understated. Escalated costs are also provided for the mission profile as per standard practice.

[18] ORP-11242 (Rev. 9) provides an overview of the Hanford system planning process and the TOPSim and lifecycle cost model.

In support of this study, the WRPS Mission Integration Analysis group performed a TOPSim model run and developed a lifecycle cost profile for alternative Grout 4B (off-site grout with off-site disposition). TOPSim process logic input was developed from the process alternative description provided in Volume II, Appendix C, Section C.13. For the run to be completed, HLW process logic was also needed. This logic was taken directly from the Vitrification 1 (modified) modeling effort.

The LAW and HLW logic flows, as shown in Table F-11 and Table F-12, describe the processing sequence for the waste in the various sections of the tank farms and what systems are available for processing. Essentially, this logic describes how tank space is managed in conjunction with process operations, waste feed preparation and delivery, and retrievals throughout the mission simulation.

As shown in Table F-11, **LAW Phase 1** describes the DFLAW vitrification phase – the preferential process throughout the mission. **LAW Phase 2** describes TSCR pretreatment/off-site processing for the S, SX, and U Farm tanks. These LAW phases are common between alternative Grout 4B and the Vitrification 1 (modified) model run. **LAW Phase 3** is initiated once the currently operating (as of February 2022) TSCR is replaced by the 3× expansion TFPT system. This phase describes collecting and delivering all feed in excess of LAW vitrification capacity for off-site grouting and disposition.[19] **LAW Phase 4** is the expansion of pretreatment operations and off-site disposition capacity to support HLW operations.

Table F-11. Low-Activity Waste Supplemental Treatment Alternative 4B – Low-Activity Waste Feed Processing (Overview Input Language for the TOPSim Model Run)

LAW phase	Start year	End year	Phase overview
Phase 1	2023	2064	• DFLAW process using southeast TSCR facility to pretreat supernatant liquid in southeast quadrant (A/AX/C Farm SSTs and 200 East Area DSTs) and send to WTP LAW Vitrification Facility; continues through end of the mission
Phase 2	2026	2058	• New southwest TSCR comes online to pretreat supernatant liquid in southwest quadrant (S/SX/U Farm SSTs and SY Farm DSTs) before sending for supplemental treatment • Southwest TSCR runs until all 200 West Area SSTs have been retrieved
Phase 3	2028	2064	• Southeast TFPT (3× TSCR capacity) and LAW feed evaporators for both southeast and southwest TSCRs come online; evaporators concentrate pretreated feed to 7.5 M sodium through end of the mission • Any LAW feed in excess of what can be treated by WTP LAW Vitrification is then sent for supplemental treatment and continues through the end of the mission • B complex retrievals begin as space opens in southeast quadrant
Phase 4	2036	2064	• Southeast TFPT capacity and supplemental LAW treatment increase so HLW vitrification paces the mission

Note: These instructions are specific to the processing of LAW feed. Phase 1 defines DFLAW as the preferred feed pathway for the mission. This logic is inherent to all alternatives developed for this study.

DFLAW = direct-feed low-activity waste.
DST = double-shell tank.
HLW = high-level waste.
SST = single-shell tank.
TFPT = tank farms pretreatment.
TSCR = tank-side cesium removal.

LAW Phases 3 and 4 differ from the Vitrification 1 (modified) logic. Vitrification 1 (modified) relies on LAW Phases 1 and 2 until the LAW supplemental treatment vitrification facility comes online in 2050. This difference is what defines the timing and sequencing of tank retrievals, DST space management, and HLW process support.

[19] LAW Phase 3 includes on-site evaporation for 200 East and West Area processing. This is included in the modeling and cost estimating.

Note that logic identifying SST retrievals – notably in LAW Phase 2 (S/SX/U Farms) and LAW Phase 3 (B/BY/BX Farms) – and for supporting HLW processing is required within the LAW process logic. The mission is inherently integrated.

Table F-12 describes the process logic and sequence for HLW processing. As described, these phases are common between alternative Grout 4B and the Vitrification 1 (modified) model runs. The HLW process attainment and mission pace do differ as a function of DST space availability per the total LAW feed work-off.

Table F-12. Low-Activity Waste Supplemental Treatment Alternative 4B – High-Level Waste Feed Processing (Overview Input Language for the TOPSim Model Run)

HLW phase	Start year	End year	Phase Overview
Phase 1	2033	2050	• HLW feed pretreatment in existing DSTs: solids/liquids separation by settling/decanting, solids washing, characterization/staging • Delivered to HLW Vitrification Facility starting in 2033 and continues through the end of the mission
Phase 2	2036	2050	• Caustic leaching performed as necessary for HLW pretreatment operations in the existing DSTs • Once space is available in the 200 East Area DSTs, slurry from the southwest quadrant transferred to the southeast quadrant
Phase 3	2050	2066	• HFPEM Facility with cross-flow filtration and evaporation capabilities comes online to replace HLW preparation operations in existing DSTs • Washing and caustic leaching now also occur in the HFPEM

Note: These instructions are specific to the processing of HLW feed and provide for direct comparison between alternative Grout 4B and the Vitrification 1 (modified) (vitrification start-up in 2050) model run referred to in this study.
DST = double-shell tank. HLW = high-level waste.
HFPEM = High-Level Waste Feed Preparation and Effluent Management.

To illustrate the difference in cost magnitude between vitrification and grouting options, WRPS performed TOPSim simulations to estimate the annual costs of construction and operations for an alternative similar to Vitrification 1 and an alternative similar to Grout 4B – referred to here as "Vitrification 1 (modified)" and "Grout 4B Early Off-site Disposition". Those model runs cover the entire Hanford tank waste mission (HLW, LAW, plus LAW supplemental treatment). These simulation results (summarized in Figure F-4 and Figure F-5) show the WRPS estimated breakout of these costs by WBS element.

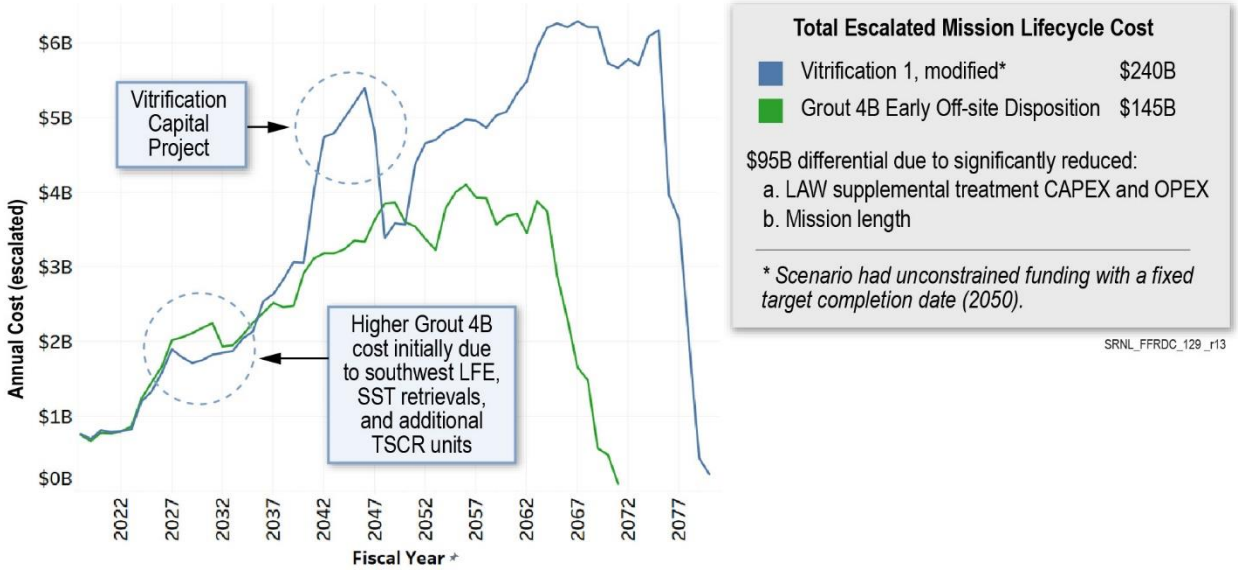


Figure F-4. Annual Mission Cost Profile Comparison between Unconstrained Funding of Alternatives Grout 4B and Vitrification 1 (Modified)

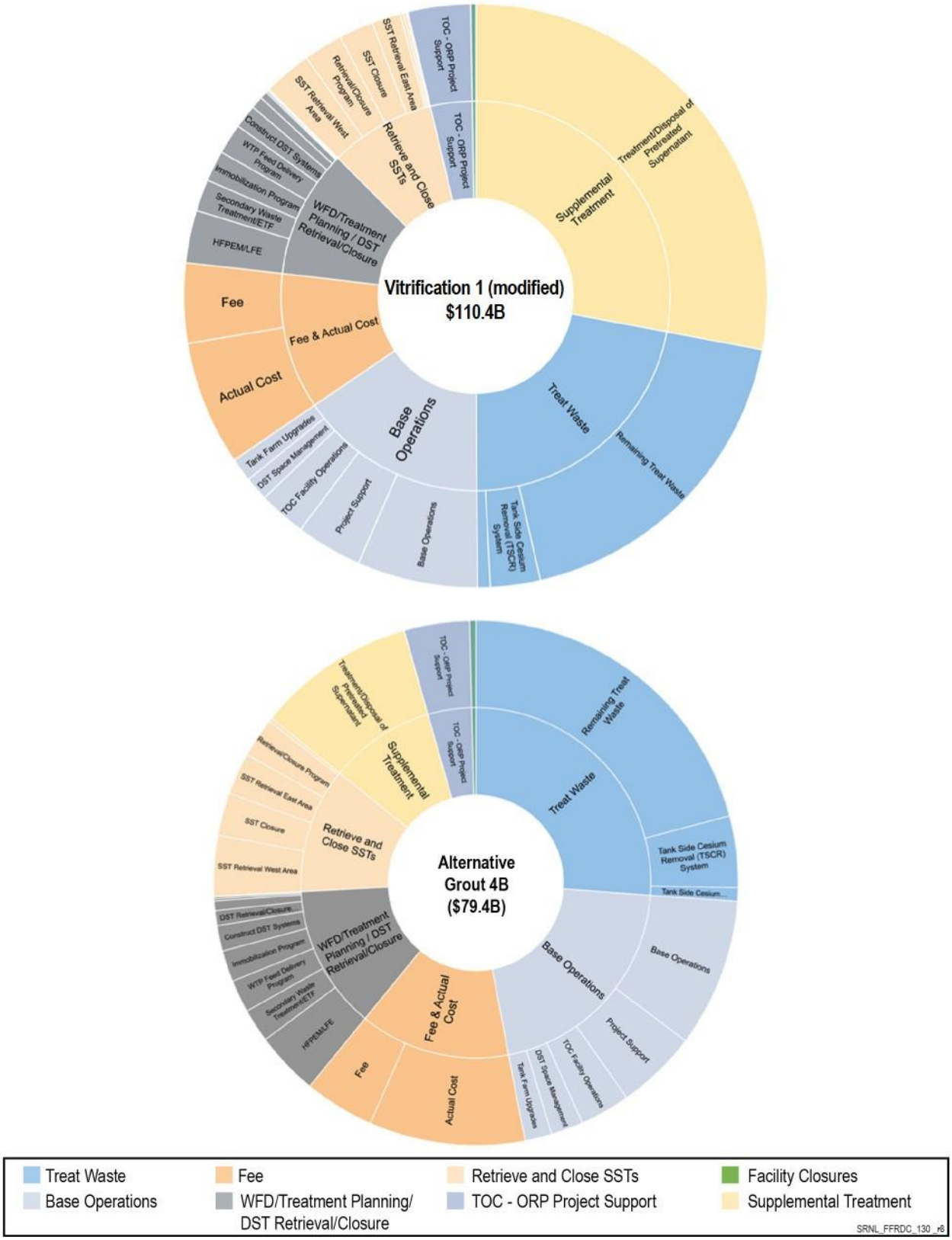


Figure F-5. Cost Elements (Unescalated) by Work Breakdown Structure – Alternative Grout 4B and Vitrification 1 (Modified)

The mission schedule and cost differential for the two scenarios demonstrates the impact of fully supporting the HLW mission, and the capital avoidance and lower annual operating costs. The grout option reduces the HLW mission duration by 9 years (2034 through 2066 versus 2034 through 2075), or approximately 25%. The mission cost is reduced $30 billion (unescalated) or $95 billion (escalated at 2.4%, including capital projects).[20] Again, this is primarily due to fewer years of process operations, lower LAW supplemental treatment annual costs, and capital avoidance.

Figure F-5 (on previous page) provides a summary, comparative view of costs (unescalated) by work element. These "wheel" diagrams provide perspective on the relative cost of work elements. The single largest element per Vitrification 1 (modified) is LAW supplemental treatment – greater than all of WTP or combined retrieval/closure and waste feed preparation. When off-site grout is the LAW supplemental treatment pathway, this work element is significantly smaller in both absolute cost (versus vitrification) and relative to WTP, retrievals/closure, or waste feed preparation. Note that the wheels are also sized to show the total project cost.[21] The $30 billion (unescalated) cost differential is effectively half due to the lower LAW supplemental treatment portion and half due to the reduction in the mission duration.

Table F-13 illustrates the impact of LAW supplemental treatment processing on the overall tank waste mission. As discussed in Volume I, Section 1.3.1.2, HLW and LAW processing are highly integrated. Early off-site grout significantly improves the metrics for HLW canister production, pretreatment system requirements, and retrieval completion, in addition to mission cost. The TOPSim model provides time-step and cumulative data for treatment facility performance, the volume of waste processed, volume/mass/package count of each waste form, mission durations, and other data relevant to this analysis (similar to the data presented in Table F-13 and Table F-14 [Section F.2.3]). If this data is used in conjunction with the data in Table F-10 (Section F.2.2.6), a relative value can be established for a disposition alternative. This type of analysis is similar to that found in recent U.S. Government Accountability Office (GAO) reports (GAO-17-306, *Opportunities Exist to Reduce Risks and Costs by Evaluating Different Waste Treatment Approaches at Hanford*, and GAO-22-104365, *Actions Needed to Enable DOE Decision That Could Save Tens of Billions of Dollars*) and can be used to compare these types of studies and provide a common reference point for decision-makers.

Table F-13. Tank Waste Mission Performance and Cost Metrics – Alternative 4B and Vitrification 1 (Modified)

	Alternative 4B Early Start Offsite Grout	Vitrification 1 (modified) (2050)
Treat all tank waste (calendar year)	2066	2075
HLW canisters produced	9,300	12,000
Maximum TSCR pretreatment required	5	8
Completions SST retrievals	2057	2070
Unescalated cost	$79B	$110B
Total escalated lifecycle cost	$145B	$240B

HLW = high-level waste.
LAW = low-activity waste.
SST = single-shell tank.
TSCR = tank-side cesium removal.

[20] In general, escalated dollars are not added across multiple years, however; to allow for comparisons against past estimates (that were reported in escalated dollars) for the RPP mission, including LAW supplemental treatment, they are provided in addition to discounted (present value) dollars. In addition, this study uses 4% or 8% escalation for capital projects versus the 2.4% value used within the lifecycle cost model. As such, the peak in Figure F-4 reflecting LAW supplemental treatment is significantly conservative versus more realistic project cost escalation (e.g., 4 to 8%).

[21] Unescalated costs are used in the Figure F-5 diagrams as not all costs reflect the same mission timeframe. For example, SST retrievals will always need to proceed processing and often conclude nominally a decade in advance of mission completion.

Table F-14 provides an additional view of relative mission performance based on the startup and operations of LAW supplemental treatment. If delayed to 2050, the vitrification process will disposition less than 20% of the technetium inventory – less than half that achieved by off-site grouting from the 200 East Area. This is not only due to the late start date but also due to the concentration of technetium in the remaining waste. As a result, the vitrification option delivers a total of 16,000+ Ci of technetium to IDF, whereas the grouting option is consistent with over 18,000 Ci dispositioned offsite, permanently away from the Columbia River Corridor. These values are both set against the current inventory of approximately 25,000 Ci.

Table F-14. Technetium-99 Curie Disposition – Alternatives 4B and Vitrification 1 (Modified)

Disposal	Waste Type	Treatment	Alternative 4B Ci Tc	Vitrification 1 (modified) Ci Tc
Offsite	LAW	200 West TSCR	6,500	7,500
Offsite	LAW	200 East TSCRs	10,500	N/A
Onsite	LAW	LAW vitrification	6,800	11,900
Onsite	LAW	Supplemental LAW vitrification	N/A	4,400
Offsite	HLW	HLW vitrification	1,250	1,250
		Total	**25,050**	**25,050**

Notes: Tank farm inventory **25,000 Ci**
Expected loss 1%
HLW nominal content 5% (1,250 Ci)

HLW = high-level waste.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
Tc = technetium.
TSCR = tank-side cesium removal.

Summary Technetium Disposition

Off-site Grout 4B		Vitrification 1 (modified)
18,250	Total offsite (Ci)	8,750
6,800	Total on-site IDF (Ci)	16,300

Several key parameters are worth noting. A primary result is the reduction of mission completion from 2075 (Vitrification 1 [modified]) to 2066 (Grout 4B). This is accomplished due solely to the DST space generated by LAW supplemental treatment being used for HLW feed preparation, resulting in a 20% reduction in HLW canisters. At the same time, additional space generated by LAW supplemental treatment is sufficient to allow SST retrievals to complete 13 years earlier (2057 versus 2070).

The improved retrieval and processing schedule allows for significantly faster risk reduction – as shown by the technetium and iodine removal curves in Figure F-6. These results indicate that the timing for LAW supplemental treatment can have major mission impacts, consistent with the implications shown previously in Figure F-1 and Figure F-2.

An additional impact, referring to long-term risk reduction, is also provided. By using an off-site grout option to support DST operations, less than 30% of the total technetium inventory will be disposed in IDF.

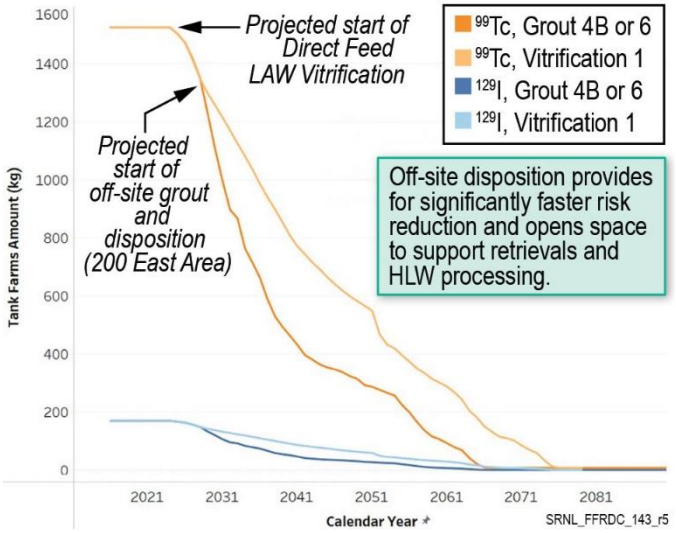


Figure F-6. Technetium and Iodine Removal (Grout 4B/6 and Vitrification 1)

In the Vitrification 1 (modified) scenario, this value is in excess of 65% and would exceed 90% if the small amount of off-site disposition required to assist 200 West Area SST retrievals was not employed (Figure F-7).

For this particular comparison, the mission cost reduction – $30 billion (unescalated) or $95 billion (escalated), is achieved specifically by supporting tank farm operations and HLW vitrification. In this manner, on-site disposal of technetium and mission length are simultaneously reduced.

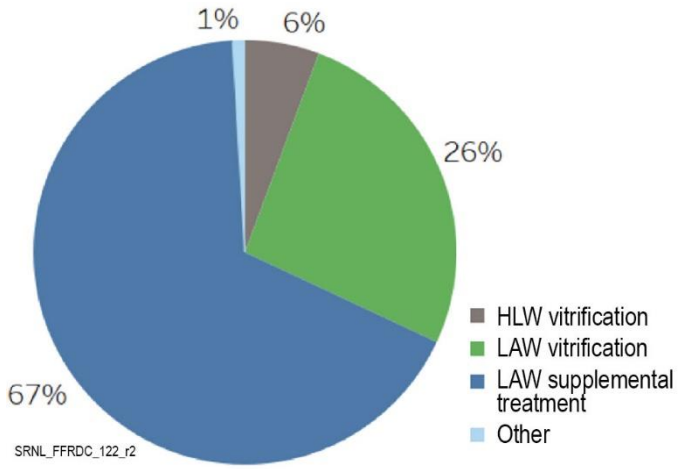


Figure F-7. Technetium Disposition per the Grout 4B Simulation (LAW Supplemental Treatment as Off-site Grout and Disposition)

F.2.4 Evaluation of Process Alternatives

This study, together with the System Planning TOPSim and lifecycle cost data, can be used to show cost and risk reduction-related parameters. The alternatives shown in Table F-15 reflect the timing and integration of LAW supplemental treatment into the tank waste clean-up mission. LAW supplemental treatment is needed to increase the work-off rate of the tank waste volume to support the overall retrieval/storage/preparation system capacity to allow HLW vitrification to effectively pace the RPP clean-up mission. This function is the reason LAW supplemental treatment was first proposed. The start-up and operations of LAW supplemental treatment have a significant impact on the overall mission, as demonstrated by the previously discussed TOPSim results in Table F-13 and Table F-14, and Figure F-4 and Figure F-5, which are described in more detail below.

The relationship between incurred cost at the projected performance within the soon-to-start (2023) tank waste clean-up mission for the five alternatives is shown in Table F-15.[22]

Process costs incurred (unescalated) are provided through 2033 (start-up of HLW vitrification), 2039 (projected start-up of alternative FBSR 1A), 2047 (projected start-up of alternative Vitrification 1), and through mission completion. The projected volume of LAW feed processed and estimated curies of ^{99}Tc dispositioned by the treatment alternative are also listed for these dates. The volumetric feed consumed by each alternative will approach or exceed 90 Mgal[23] However, there is a significant difference among alternatives regarding potential technetium disposition. This is due to the concentration of technetium in the initial LAW feed. This feed is currently the supernatant liquid in the DSTs and is significantly enriched in soluble technetium versus the precipitated salt in the SSTs.[24] In effect, while the volumetric reduction capabilities of LAW supplemental treatment are closely tied to the overall mission duration, the disposition of technetium is more closely connected to the initiation of LAW feed consumption.

[22] The TSCR unit constructed to support the DFLAW program started to generate feed in February 2022.

[23] The volumetric feed value is based on the Vitrification 1 and Grout 4B modeling runs as performed using the TOPSim model – assuming the CST ion exchange pretreatment as performed at nominally 5.5 M sodium. This volume is recognized to be higher than many of the System Plan (ORP 11242, Rev. 9, and previous) options, which assume operation of the WTP PT Facility with elutable resin and 7+ M sodium feed. Differences in feed volume between the alternatives in this study are due to differences in the LAW supplemental treatment start dates.

[24] Technetium is distributed in the various quadrants based on the plutonium separations facility location and mission timing. Technetium in the northwest and northeast quadrants is derived from T and B Plant operations, respectively. These plants operated from the Manhattan project era and effectively split the incoming fuel (technetium source) through 1956. A small amount of technetium was processed through the REDOX plant located in the southwest quadrant. From 1956 on, the majority of fuel was processed at the PUREX plant, with fission products distributed throughout the southeast quadrant.

Table F-15. Comparison of Cost and Projected Performance of Low-Activity Waste Supplemental Treatment Alternatives

LAW Supplemental Treatment Alternative	Cumulative unescalated cost | Constant FY 2023 value ($M, rounded)				Cumulative gallons of supplemental LAW feed treated (Mgal)				Cumulative curies of technetium treated (Ci)			
	2033[a]	2039[b]	2047[c]	At Treatment Alternative Mission End[d]	2033[a]	2039[b]	2047[c]	At Treatment Alternative Mission End[d]	2033[a]	2039[b]	2047[c]	At Treatment Alternative Mission End[d] (percent of technetium treated)
Vitrification 1 (on-site facility with IDF disposition)	2,200 | 4,100	5,600 | 6,800	8,100 | 10,400	23,400 | 27,000 [2075[d]]	-	-	-	83[e]	-	-	-	6,640 (27%)
FBSR 1A (on-site facility with IDF disposition)	1,600 | 2,100	3,500 | 4,600	4,800 | 5,900	8,400 | 9,900 [2070[d]]	-	-	25	86[e]	-	-	5,700[e]	10,210 (41%)
Grout 1A (on-site facility with IDF disposition)[ff]	1,100 | 1,200	1,600 | 1,800	2,500 | 2,700	4,600 | 5,000 [2068[d]]	-	13	37	92[e]	-	4,500	11,000	15,100 (62%)
Grout 4B (off-site grout with off-site disposition)	1,300 | 1,300	2,500 | 2,600	4,000 | 4,100	6,400 | 6,900 [2066[d]]	14	34	58	97	6,900	10,100	12,600	17,000 (68%)
Grout 6 (off-site grout with off-site disposition through 2039; on-site facility with GDU disposition 2040 on)	1,400 | 1,600	3,200 | 3,600	4,100 | 4,800	5,800 | 6,900 [2066[d]]	14	34	58	97	6,900	10,100	12,600	17,000 (68%)

[a] Key mission activity: 2033 – Start of HLW vitrification (assumed end of year).
[b] Key mission activity: 2039 – Start of FBSR for supplemental LAW treatment (assumed end of year).
[c] Key mission activity: 2047 – Start of vitrification for supplemental LAW treatment (assumed end of year).
[d] The mission end date varies by treatment technology.
[e] For alternative Grout 4B, the technetium curies dispositioned are taken directly from the TOPSim model run. Alternative Grout 6 is assumed to have the same feed vector – understanding that technetium treated from 2040 on (6,000 Ci) would be dispositioned onsite in IDF versus offsite. For alternative Vitrification 1, the technetium curies treated are adjusted from the Vitrification 1 (modified) TOPSim model run by adding 3× the nominal technetium curies treated by LAW vitrification over that same period. Technetium treated by dates for alternatives FBSR 1A and Grout 1A were similarly projected based on nominal LAW vitrification technetium performance – assuming the alternatives would see the same feed vector as LAW vitrification. Projected volumes for process alternatives were calculated in a similar manner using the annual feed volumes projected for the process alternatives in this study and bounded by the TOPSim modeling results.
[f] Grout 1A is included in this chart to reflect the performance with respect to gallons of supplemental LAW treated and curies treated. Grout 1A is consistent with all Grout 1, 2, 3, and 5 process feed vectors.

Ci = curie.
FBSR = fluidized bed steam reforming.
FY = fiscal year.
GDU = grout disposal unit.
HLW = high-level waste.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
Mgal = million gallons.
Tc = technetium.

For reference, the LAW Vitrification Facility will process nominally 10,000 Ci of technetium the first 27 years of operations (2023–2050) during the Vitrification 1 (modified) TOPSim model run scenario, but just under 2,000 Ci of technetium in the final 25 years (2050–2075).

This concept is important as it demonstrates a diminishing return on technetium disposition versus volume processed. As the mission progresses from feed currently stored as supernatant liquid to feed derived from SST retrievals, there is noticeable reduction in technetium concentration. Figure F-8 provides a graphic example of the cost versus ^{99}Tc curies dispositioned at the end of mission. The LAW supplemental treatment technologies will all process between 80 and 100 Mgal of LAW feed. Alternatives with deferred starting dates will ultimately disposition fewer technetium curies via LAW supplemental treatment, and force longer, higher cost missions. From that basis, Alternative Vitrification 1, with the highest cost by a nominal factor of three and a disposition of one-third of the technetium curies, provides a significantly lower rate of return (based on curies and/or cost) than any other alternative.

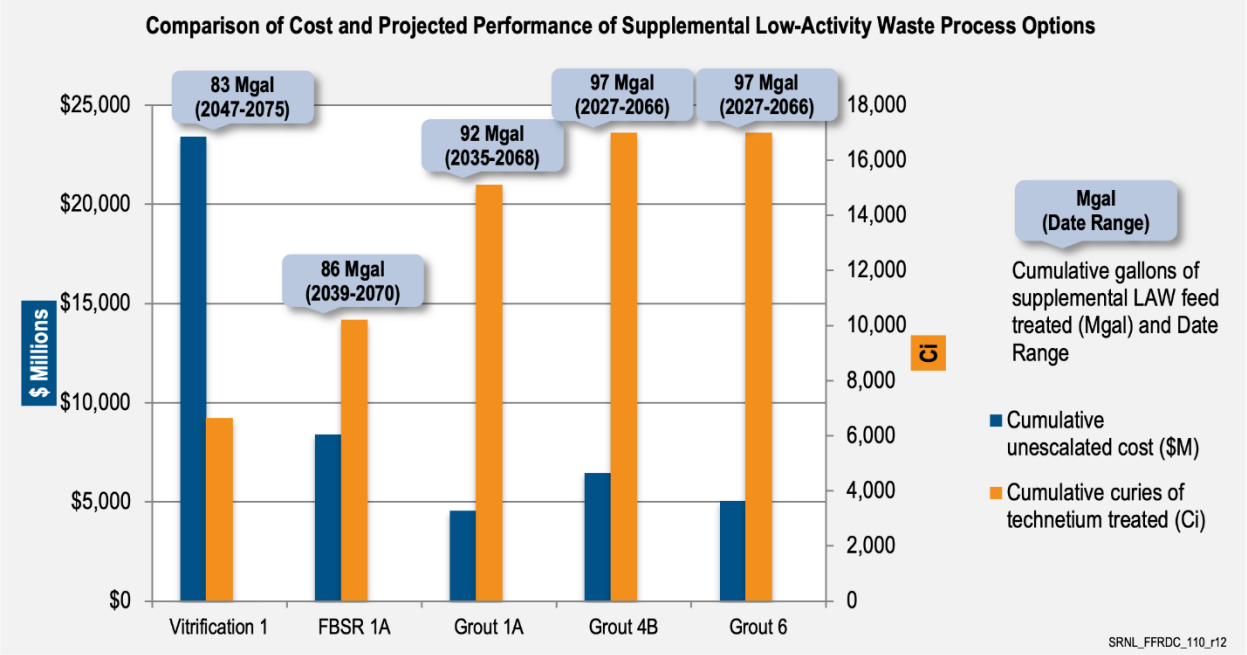


Figure F-8. Comparison of Cost (Unescalated) and Projected Performance of Supplemental Low-Activity Waste Process Options

Figure F-9 and Figure F-10 illustrate the necessary funding for the four non-vitrification alternatives.[25] These figures reflect the cost to support these projects in the event that 8% escalation for CAPEX, a worst-case scenario, is applied. Grout 1A is the lowest cost alternative throughout the mission. Initially, Grout 4B is significantly less than Grout 6, which must provide for facility construction in addition to off-site disposition.

[25] Figure F-9 and Figure F-10 provide annual projections consistent with the summary point values provided in Table F-10.

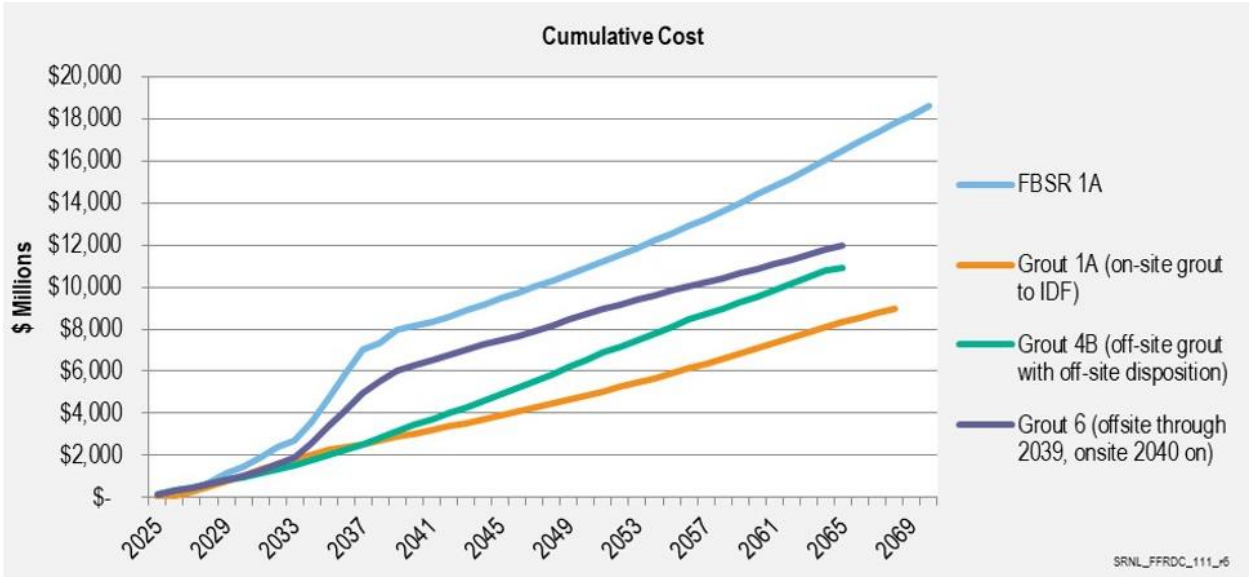


Figure F-9. Cumulative Cost (Escalated) for Fluidized Bed Steam Reforming and Grout Alternatives

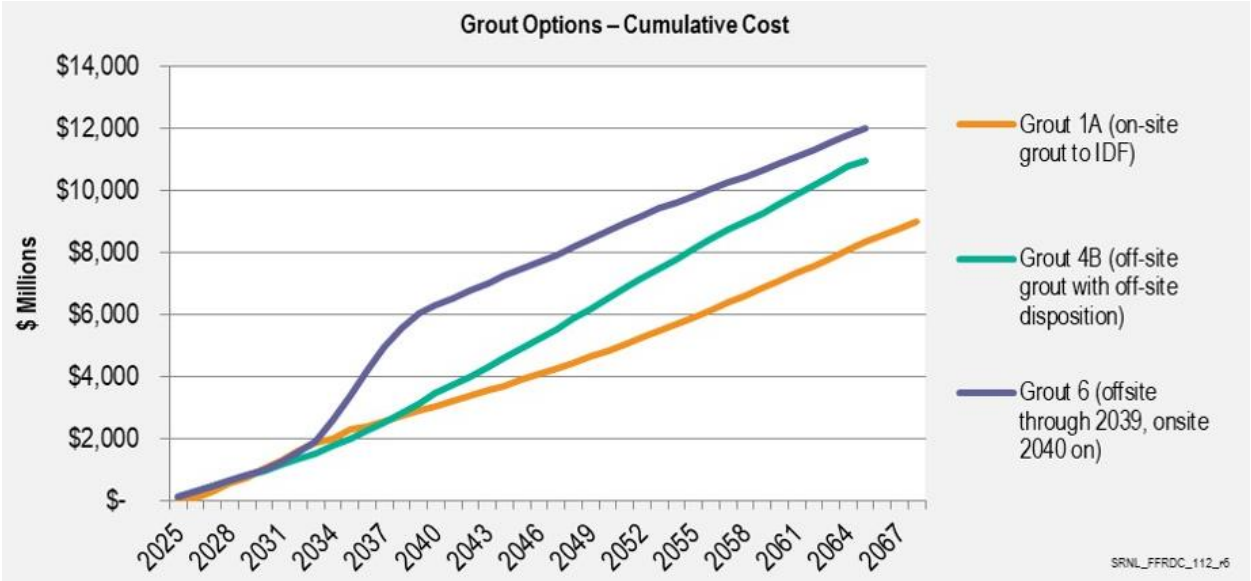


Figure F-10. Cumulative Cost (Escalated) for Grout Alternatives

As the mission progresses into the 2050s and beyond, alternatives Grout 1A and 6 demonstrate lower operations costs. Note that the off-site grouting cost used for Grout 6 and Grout 4B is the lower cost per gallon ($30 versus $45/gallon). Increasing the cost of off-site grout to the higher cost will shift Grout 4B above the line defined by Grout 6 – as Grout 6 provides for on-site (GDU) disposition of grout post-2039.

The near-term timeframe (through 2040) demonstrates separation of the options. Within that period, FBSR appears more costly to construct than to (1) construct and operate an on-site grout plant to disposition 10+ Mgal and ≈4,500 Ci of ^{99}Tc, or (2) disposition 30+ Mgal and ≈10,000 Ci of ^{99}Tc offsite.

F.3 EFFECTS OF DISCOUNTING ON THE DECISION FRAMEWORK

The following steps were performed to determine the present value of lifecycle costs of the various alternatives for purposes of assessing Criterion 4:

1. Establish a benchmark annual budget of $450 million in constant FY 2023 dollars
2. Inflate that annual budget at 2.1% annually to get the escalated (then-year) budget expected to be available in each year
3. Estimate the cost of each alternative in unescalated (current price) dollars
4. Escalate those costs using appropriate escalation rates for construction and for operations
5. Adjust each estimate to fit construction within the cumulative escalated budget, pushing work into the future (with appropriate escalation) as necessary
6. Deflate the annual costs using the 2.1% inflation rate, to get annual cost estimates expressed in constant FY 2023 dollars (Table F-16)
7. Discount the annual constant dollar estimates, using a discount rate of 3%, to get the present value of the costs in each year (Table F-17)
8. Add up these discounted costs to calculate the total present value of pre-operations and operations expenditures, and report these values under Criterion 4.

Table F-16. Total Constant Year (FY 2023) Option Costs

Alternative	Hot Operations[a]	LAW Supplemental Treatment Complete	Total Project Cost $M	Total OPEX Cost $M
Vitrification 1	2050	2075	**$ 27,243**[b]	**$ 15,434**
FBSR 1A	2040	2070	**9,927**	**5,237**
FBSR 1B	2040	2070	**11,744**	**7,032**
Grout 1A	2036	2068	**5,019**	**3,576**
Grout 1B	2036	2068	**6,515**	**5,056**
Grout 1C	2036	2068	**5,794**	**4,222**
Grout 2A	2036	2068	**6,137**	**4,131**
Grout 2B	2036	2068	**8,171**	**6,134**
Grout 2C	2036	2068	**7,089**	**4,953**
Grout 4A	2027	2065	**5,899**	**5,477**
Grout 4B	2027	2065	**6,860**	**6,429**
Grout 5A	2036	2068	**6,074**	**4,364**
Grout 6	2027	2065	**6,869**	**5,891**

[a] Note: There may be a discrepancy for the hot operations commencing dates between this table and previous charts. For the purpose of assessing Criterion 4 (lifecycle costs), a clear delineation between capital and operations was required. This adjustment is considered well within the uncertainty of cost/schedule projections.

[b] As stated previously, Vitrification 1 operations are projected to be in excess of $450 million annually. For this exercise, the projected funding required was included for OPEX calculations and in the total.

OPEX = operations expenditure.

Table F-17. Total Discounted Cost and OPEX Cost

Alternative	Hot Operations[a]	LAW Supplemental Treatment Complete	Total Cost Discounted (3% basis) $M	Total OPEX Cost Discounted (3% basis) $M
Vitrification 1	2050	2075	**$ 12,700**[b]	**5,092**
FBSR 1A	2040	2070	**5,527**	**2,152**
FBSR 1B	2040	2070	**6,279**	**2,905**
Grout 1A	2036	2068	**2,730**	**1,622**
Grout 1B	2036	2068	**3,414**	**2,306**
Grout 1C	2036	2068	**3,115**	**1,915**
Grout 2A	2036	2068	**3,395**	**$ 1,851**
Grout 2B	2036	2068	**4,318**	**$ 2,774**
Grout 2C	2036	2068	**3,847**	**$ 2,211**
Grout 4A	2027	2065	**3,338**	**$ 2,927**
Grout 4B	2027	2065	**3,854**	**$ 3,444**
Grout 5A	2036	2068	**3,349**	**$ 1,614**
Grout 6	2027	2065	**4,127**	**$ 2,734**

[a] Note: There may be a discrepancy for the hot operations commencing dates between this table and previous charts. For the purpose of assessing Criterion 4 (lifecycle costs), a clear delineation between capital and operations was required. This adjustment is considered well within the uncertainty of cost/schedule projections.

[b] As stated previously, Vitrification 1 operations are projected to be in excess of $450 million benchmark funding annually. For this exercise, the projected funding required was included for OPEX calculations and in the total.

OPEX = operations expenditure.

Federal guidance for the assessment of proposed expenditures of public funds (and for proposed regulatory actions) requires that foreseeable costs and benefits of the proposed project or program be discounted over time. Current U.S. Office of Management and Budget (OMB) guidance specifies a 7% annual real discount rate for capital expenditures (OMB Circular A-94, "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs," page 9). However, associated guidance allows for a lower discount rate of 3% annual real discounting for non-monetizable benefits (OMB Circular A-4, "Regulatory Analysis," page 33). That guidance also notes that, in the case of intergenerational costs and benefits, a lower real rate (between 1% and 3%) may be appropriate (OMB Circular A-4, page 36). The projected timelines for treatment of supplemental LAW, particularly for the Vitrification 1 alternative, qualify as intergenerational. For that reason, the FFRDC team chose to apply a discount rate of 3%.

Because the costs and benefits associated with Criterion 1 (long-term effectiveness) are identical across all alternatives until several centuries in the future, discounting has a profound impact on the tradeoffs between Criterion 1 and the other criteria. Even at 1% discounting, one dollar of harm next year would be assessed as equivalent to $145 (FY 2023 dollars) of harm 500 years from today, or $21,000 (FY 2023 dollars) of harm 1,000 years from today. As a result, the estimated differences in long-term performance across the range of evaluated alternatives are insignificant when discounting is applied. For any nonzero discount rate, the total discounted costs and benefits associated with differences in waste form performance are completely dominated by costs, benefits, and risks incurred during construction and operations. The discounted (from LAW supplemental treatment complete back to 2023) cost per Criterion 4 is summarized by alternative (Base Case) in Table F-17. Additionally, the discounted cost (2023 basis) of LAW supplemental treatment operations is also provided.

As per the above analysis based on escalated/non-escalated mission costs, Vitrification 1 is shown to be more expensive when viewed on a discounted cost basis with regard to total, capital, and/or operations. The FBSR alternatives are more closely comparable to the Grout alternatives, but still display a higher cost with respect to on-site disposal (waste packages to IDF or vaults) or off-site disposal (to the Waste Control Specialists [Texas] and/or Energy*Solutions* [Clive, Utah] disposal facilities) than the Grout alternatives.

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Appendix G. Disposal Sites

G.1 INTRODUCTION

The low-activity waste (LAW) immobilized by the alternatives described in this report will be permanently disposed of either on or off the Hanford Site. A combination of on-site and off-site disposal is also plausible (alternative Grout 6). This appendix describes the available disposal options for the Hanford LAW requiring supplemental treatment. Section G.2.1 describes on-site disposal at the Hanford Integrated Disposal Facility (IDF). Two off-site disposal facilities were identified as potential disposal sites – Energy*Solutions* Clive facility in Utah (Section G.2.2) and the Waste Control Specialists, LLC (WCS) facility in Texas (Section G.2.3). The off-site disposal of all supplemental LAW is assumed in alternatives Grout 4B and fluidized bed steam reforming (FBSR) 1B (FBSR 1B was considered, but not recommended). The off-site disposal of grout generated until 2040 is assumed in alternative Grout 6. The grout generated starting from 2040 is assumed to be disposed of onsite in this alternative. The off-site disposal of all grout generated in alternative Grout 6 was considered to cover the unlikely situation in which on-site disposal becomes unavailable. Note that the liquid-to-solid volumetric ratio was conservatively assumed to be 1.2 in transport and disposal calculations related to FBSR. The larger ratio results in a larger FBSR waste volume. The FBSR volumetric ratio assumed in all other analyses discussed in this report was 1.0.

As described in Volume II, Appendix H, Section H.6, all supplemental LAW liquids converted to solid waste forms, either grout or FBSR, can be disposed of at WCS. Class A waste, which includes 83% to 90% of the grout and 72% of FBSR waste forms, can be disposed of either at WCS or Clive. This conclusion was made based on the comparison of (1) the radionuclide composition of grout and FBSR waste forms to the Clive and WCS radiological waste acceptance criteria (Appendix H, Section H.6.1), and (2) the Class A waste volume to Clive and WCS available disposal volumes (Appendix H, Section H.6.2). Note that the radiological waste acceptance criteria are identical at WCS and Clive; waste classified as Class A at Clive would be classified as Class A at WCS. Details of the waste class determination are provided in Appendix H, Section H.6.

The details regarding transport of the different waste forms (liquids, grout, and FBSR) to Clive and WCS are discussed in Volume II, Appendix H. The conclusion made in Appendix H is that the liquid, grout, and FBSR waste forms meet all the requirements of the low-specific activity (LSA)-II materials and are exempt from classification as fissile material. Consequently, liquid, grout, and FBSR waste forms can be transported in industrial packages (e.g., IP-2 or IP-3) that are exempt from U.S. Nuclear Regulatory Commission (NRC) certification. The proposed packaging is described in Appendix H, Section H.7.1.

Liquids, if transported to Clive and/or WCS, are assumed to be treated at Clive or WSC to generate a grout waste form. Volume II, Appendix H also discusses how splitting the Class A waste between the Clive and WCS facilities affects transportation and disposal costs.

G.2 DISPOSAL SITES

This appendix describes three disposal facilities that are under consideration for disposal of Hanford supplemental LAW.

- **Integrated Disposal Facility (IDF)** (Hanford Site) – A U.S. Department of Energy (DOE) facility that is permitted by the Washington State Department of Ecology (Ecology) for disposal of low-level waste (LLW) and mixed LLW (MLLW) from Hanford Site operations.
- **Energy*Solutions* Disposal Facility** (Clive, Utah) – This disposal facility is commercially operated by Energy*Solutions* and is licensed by the state of Utah (an NRC Agreement State) and the U.S. Environmental Protection Agency (EPA) to dispose of LLW and MLLW. The Clive facility can accept only Class A LLW and MLLW for disposal.

- **Waste Control Specialists (WCS) Waste Disposal Facility** (Andrews, Texas) – This disposal facility is commercially operated by WCS and is licensed by the state of Texas (also an NRC Agreement State). The WCS facility can accept Class A, B, and C LLW and MLLW for disposal.

The NRC Agreement States use state versions of the 10 CFR 61, "Licensing Requirements for Land Disposal of Radioactive Waste," standard for licensing LLW disposal facilities, which divides LLW into "classes," with Class A and C wastes as the least and most hazardous, respectively.

The Clive and WCS facilities can safely dispose of wastes containing the projected LAW concentrations of iodine-129 (^{129}I) and technetium-99 (^{99}Tc). This conclusion is based on in-depth analysis of the disposal performance.

The description of the disposal sites is focused on the site conditions, disposal facility design, applicable regulations, waste acceptance criteria, and analyses performed in support of the disposal performance assessment (PA). The other aspects are discussed in Volume II, Appendix H.

G.2.1 Integrated Disposal Facility (Hanford Site, Washington)

Description

The IDF is located in the 200 East Area of the Hanford Site in Washington State and provides a disposal facility for LLW and MLLW. The Hanford Site is located within the Columbia Plateau between the Cascade Range and the Rocky Mountains. This portion of the plateau is also known as the Columbia Basin, as it is a topographically low area surrounded by mountains on all sides. Cataclysmic ice age flooding inundated the area, depositing sediment that is informally called the Hanford formation. The underlying basalts form a block of rock that is surrounded by active fault zones where stresses are mostly relieved. Therefore, stress relief and ground motion on the Columbia Plateau are relatively small. Table G-1 provides the general stratigraphy of the Hanford Site (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington).*

Table G-1. General Stratigraphy of the Hanford Site

Formation	Stratigraphy
Surficial Deposits	Thin layer of silt, sand, and gravel.
Hanford Formation	Glacio-fluvial deposits from Ice Age flooding consisting mostly of unconsolidated sediments that range from pebble to cobble gravel and fine- to coarse-grained sand, with lesser amounts of silt and clay lenses.
Cold Creek Unit	Very hard rock called caliche or hardpan located primarily in the 200 West Area, but largely absent from the 200 East Area.
Ringold Formation	Semi-indurated clay, silt, fine- to coarse-grained sand, and granule to cobble gravel. Strata are typically below the water table, and textural variations can influence groundwater flow.
Columbia River Basalt Group and Ellensburg Formation	Flood-basalt flows and interbedded sediments.

Source: RPP-RPT-59958, 2019, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*, Rev. 1A, Washington River Protection Solutions, LLC, and INTERA, Inc., Richland, Washington.

The IDF is situated approximately 90 to 100 m (300 to 330 ft) above the water table, with the liner approximately 70 m (230 ft) above groundwater. Approximately 137 to 167 m (450 to 550 ft) of unconsolidated to semi-consolidated sediments over basalt bedrock underlie the disposal site. The stratigraphy at the IDF consists of the Hanford Formation and Ringold Formation. The Hanford Formation is as much as 116 m (380 ft) thick, and the Ringold Formation reaches a maximum thickness of 87 m (285 ft) on the west side of the IDF site, thinning eastward (Vance, 2021).

Constructed in 2006, the IDF comprises two expandable disposal cells (Figure G-1). Cell 1 is permitted as a dangerous waste landfill under the *Resource Conservation and Recovery Act of 1976* (RCRA), which allows for disposal of radioactive MLLW. The dangerous waste component is regulated under WAC 173-303, "Dangerous Waste Regulations," by Ecology. Cell 2 is limited to radioactive LLW only. The radioactive components of both LLW and MLLW are regulated by DOE under DOE O 435.1, *Radioactive Waste Management*. The disposal cells include a leak detection system to collect leachate (WA 7890008967, "Hanford Facility RCRA Permit").

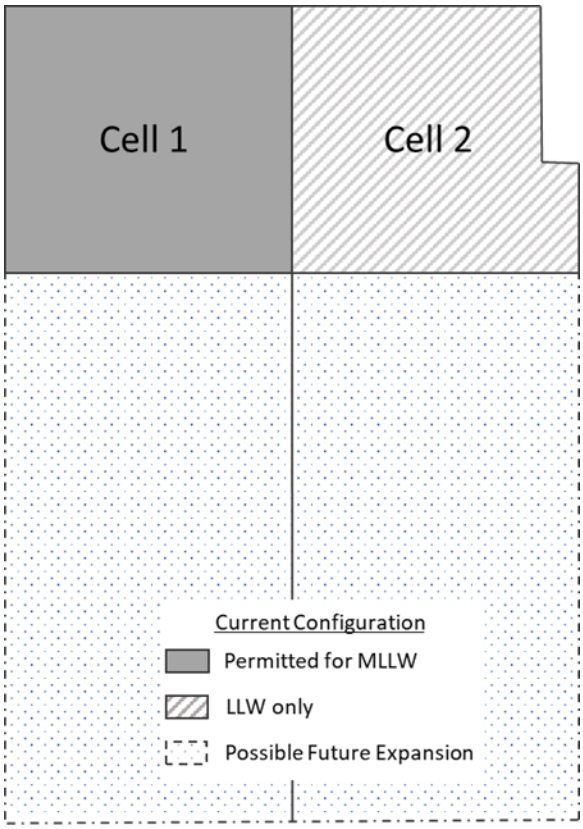


Figure G-1. Integrated Disposal Facility Configuration

Landfill Construction

The IDF liner system complies with WAC 173-303-665, "Landfills," and includes an operations layer, leachate collection and removal system (LCRS), leak detection system (LDS) and secondary leak detection system (SLDS). The operations layer, consisting of well-graded granular soil, acts as an insulating layer and protects the underlying liner from damage by equipment and from freezing and desiccation cracking.

Below the operations layer, the LCRS comprises two geotextiles and a gravel layer, followed by a geomembrane liner made of high-density polyethylene and a geosynthetic clay liner that act as moisture barriers. The LCRS is designed so that leachate flows through a perforated pipe above the primary liner into the LCRS collection sump. Below the LCRS is the LDS, which is used to collect any leachate that leaks through the LCRS. The LDS has a similar configuration, as the LCRS (except a composite drainage net) replaces the gravel layer and there is no perforated drainage pipe. The LDS geomembrane liner conveys leachate to the LDS sump for removal. The collected leachate is pumped to two leachate collection tanks until transfer to a treatment, storage, and disposal unit (WA 7890008967).

The IDF liner system also includes an SLDS, which includes an operations layer, drainage gravel, a composite drainage net, and a geomembrane. The SLDS liner is not a design requirements of WAC 173-303-665, but is a redundant leak protection system that collects any leachate that leaks through both the LCRS and LDS. Liquids in the SLDS are removed manually through a portable pump and then transferred to the leachate collection tanks. Table G-2 identifies the layout of the IDF liner system (WA 7890008967).

Table G-2. Integrated Disposal Facility Liner System Description

Layer (Top-to-Bottom)	Components (Landfill Base)	
Operations layer	• Native soil	
LCRS	• Separation geotextile • Drainage gravel • Cushion geotextile	• Primary geomembrane • Primary GCL
LDS	• Composite drainage net • Secondary geomembrane	
LDS sump	• Drainage gravel • Cushion geotextile	• Secondary geomembrane • Secondary GCL
SLDS sump	• Operations layer material • Composite drainage net	• Tertiary geomembrane
Admix layer	• 0.9 m (3-ft) thick	

Source: Vance, B.T., 2021, "Response to Technical Deficiencies for the Integrated Disposal Facility Operating Unit Group 11 Class 3 Permit Modification Request," (Letter 21-ECD-001740 to D. Bowen, Washington State Department of Ecology, June 9), U.S. Department of Energy, Hanford Site, Richland, Washington.

GCL = geosynthetic clay liner.
LCRS = leachate collection and removal system.
LDS = leak detection system.
SLDS = secondary leak detection system.

The IDF liner was completed at the north end of the landfill for the initial phase. Additional phases are anticipated to extend the liner to the south as more space for waste disposal is required. Each future liner expansion project will connect to the south edge of the previous liner (WA 7890008967).

Landfill Cover

The final cover design of the IDF has not been completed, but a general conceptual design has been developed. The general design is to cover the IDF with a modified RCRA Subtitle C barrier, which provides a surface barrier for long-term containment, hydrologic protection, and minimizes physical intrusion and recharge. A Subtitle C barrier is the baseline design for a disposal facility containing both dangerous waste and LLW. The IDF cover is anticipated to include layers composed of durable material (e.g., topsoil, sand and gravel filter, asphalt base) topped with cover vegetation and a slope (up to 5%) to encourage runoff and minimize the tendency for ponding of rainwater. These layers are intended to divert moisture that may come through the surface barrier away from the trench. The RCRA Subtitle C barrier is to be constructed with a minimum depth of at least 5 m (16.4 ft) to provide shielding from radioactive material and deter intrusion. The cover will include a vegetated surface layer of fine-grained soils to retain moisture, encourage evapotranspiration, and minimize infiltration (RPP-RPT-59958).

Key Regulatory Requirements

Disposal in IDF must meet DOE O 435.1 requirements for waste incidental to reprocessing (WIR) that specify how tank wastes that have been managed as high-level waste (HLW) are accepted for management as LLW. In addition, DOE O 435.1 requirements for near-surface disposal of LLW must be met. The LLW requirements are substantially addressed through a DOE PA that evaluates the long-term impact of near-surface disposal through computer modeling analysis, to provide DOE with a reasonable expectation that LLW and MLLW disposal will meet the radiological performance objectives documented in DOE M 435.1-1, *Radioactive Waste Management Manual*.

Performance Assessment

In 1999, the initial PA for the IDF (DOE/RL-97-69, *Hanford Immobilized Low-Activity Tank Waste Performance Assessment*) was approved, followed by an update in 2001 (DOE/ORP-2000-24, *Hanford Immobilized Low-Activity Waste Performance Assessment: 2001 Version*). Additional revisions to the PA were deferred until completion of DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC&WM EIS), which occurred in 2012. This EIS resulted in a Record of Decision (78 FR 75913, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington, Record of Decision") to implement disposal of the following waste types in the IDF:

- LLW and MLLW from tank waste treatment activities generated from the Waste Treatment and Immobilization Plant (WTP)
- On-site non-CERCLA non-tank waste
- Fast Flux Test Facility decommissioning waste
- Effluent Treatment Facility-generated solid secondary waste
- On-site waste management waste.

Based on the Record of Decision, a new PA was necessary to examine the long-term effects associated with the planned waste types. The current PA for the IDF (RPP-RPT-59958), was publicly released in 2019 and includes computer modeling of the near-surface disposal of LLW and MLLW at IDF. DOE LLW disposal requirements in DOE M 435.1-1 require that a PA "must provide reasonable expectation that the facility will not exceed the performance objectives for a period of 1,000 years following closure of the facility." The 2019 IDF PA performed analysis for the required 1,000-year period, but also from 1,000 to 10,000 years, and an extended runout to 500,000 years after closure. Computer models simulated the engineered and natural barriers of the IDF and assessed the post-closure performance objectives for exposure and performance measures of an inadvertent intrusion event. The PA assumes that the IDF will remain under institutional control for a 100-year post-closure period. The IDF PA has been reviewed and approved by DOE, and an Operating Disposal Authorization Statement has been issued (Gilbertson, 2021), licensing IDF for disposal of radioactive materials for vitrified primary waste and grouted secondary waste.

Although the most current revision of the IDF PA was completed in 2019, the technical basis supporting the PA is maintained through continued updates that evaluate changes to the PA inputs and assumptions. An annual assessment of these changes is performed to ensure that the conclusions of the PA are still valid. The description below includes the results of the PA and subsequent assessments, specifically RPP-CALC-64672, *Integrated Disposal Facility Performance Assessment Special Analysis: Updated Vadose and Saturated Zone Transport Calculations*.

Process-level models simulated the system to assess concentrations of ^{99}Tc, ^{129}I, and other radionuclides and dangerous chemicals through groundwater and air pathways. Modeling showed contribution of radionuclides and chemicals to the groundwater pathway within the 1,000-year post-closure period. This contribution is attributed to an increased ^{99}Tc inventory in grouted high-efficiency particulate air (HEPA) filters compared with the original 2019 IDF PA simulations.

Overall, groundwater models predict compliance with the 1,000-year performance objectives (compliance period). Within the 10,000-year post-compliance period, models predict compliance with performance objectives, with ^{99}Tc and ^{129}I as the primary contributing dose to a representative member of the public. The simulated base model assumes the worst possible configuration for the HEPA filter waste, disposing of it in the worst possible location in the IDF, which would place all wastes in a small area along the central portion of the facility. Mitigation options could lower the impact of radionuclides in groundwater, including the waste placement configuration and consideration of alternate methods for disposal of the HEPA filter waste stream.

For the atmospheric pathway, the 1,000-year post-closure period is dominated by the slow release and transport of gaseous radionuclides resulting in dose below performance objectives. Exposure routes include air immersion, dust inhalation, external exposure to radiation from the contaminated ground surface, and ingestion of food and animal products grown from the contaminated ground surface. The radionuclides that most significantly affect the atmospheric pathway are carbon-14 (^{14}C) and ^{129}I due to diffusion from cementitious waste forms.

Model simulations for all pathways show that the initial dose is dominated by ^{99}Tc and ^{129}I. Other radionuclides contribute insignificant doses relative to the total dose. Analysis of the 500,000-year post-closure period shows that peak doses occur in the first 10,000 years, and radium-226 (^{226}Ra) becomes a dominant contributor after 200,000 years.

In addition to assessing pathways, an analysis was performed to calculate the dose equivalent for a future member of the public that intrudes on the IDF. This type of scenario is used to establish radionuclide concentration limits for disposal. In the IDF PA intruder scenario, a hypothetical driller of groundwater uncovers waste disposed of in the IDF. The waste form is assumed to be degraded and unrecognizable. Both acute and chronic exposures were considered and evaluated for up to 1,000 years after closure of the IDF, following at least 100 years of institutional controls. Dose was calculated for the expected waste streams, and although packaging is expected for some waste streams, no additional packaging was credited in the analysis. Based on these analyses, the three chronic exposures scenarios evaluated (rural pasture farmer, suburban garden resident, and commercial farm worker) were below the 100 mrem chronic dose performance measure, and the acute well driller scenario dose was below the 500 mrem acute dose performance measure.

Waste Incidental to Reprocessing

In accordance with the criteria set forth in DOE M 435.1-1, a final WIR (DOE-ORP-2022-03, *Final Waste Incidental to Reprocessing Evaluation for Vitrified Low Activity Waste and Secondary Waste at the Hanford Site, Washington*) was prepared to address the waste from the Hanford Site underground tanks that will be separated, pretreated, and vitrified. The WIR assessed whether the vitrified waste meets the criteria in DOE M 435.1-1, and determined that the waste is incidental to reprocessing, not HLW, and may be managed as LLW. As described in the WIR, the approach removes key radionuclides, meets the 1,000-year post-closure requirements, and the vitrified waste will not exceed Class C LLW concentration limits.

Waste Acceptance

In addition, a waste acceptance criteria document for the IDF has been finalized and defines the acceptance criteria for LLW and MLLW and the requirements for complying with the IDF Disposal Authorization Statement (Gilbertson, 2021) per DOE M 435.1-1 and RCRA permit (Vance, 2020). The waste acceptance criteria prohibits HLW, which is defined in DOE O 435.1.

RCRA Permit and Waste Acceptance Criteria

The IDF is permitted as Operating Unit Group 11 under Revision 8c of the Hanford Facility RCRA Permit (number WA7890008967) (Ecology, 2022). Currently, the IDF permit authorizes disposal in only one cell (Cell 1). Cell 1 is permitted to dispose of MLLW, limited to immobilized LAW from WTP, immobilized LAW from the demonstration bulk vitrification system, and IDF operational wastes (WA 7890008967).

Currently, waste acceptance for the IDF includes the following requirements:

- Wastes must be compliant with RCRA Land Disposal Restrictions (LDR) (40 CFR 268, “Land Disposal Restrictions”).
- Transuranic wastes are prohibited.

- Free liquids are prohibited, unless one of the provisions in WAC 173-303-140(4)(b)(ii) can be met.
- Pre-waste acceptance is required; waste pedigree needs to be verified by IDF personnel.
- Containers must comply with maximum void space requirements (i.e., containers must be >90% full).

Permit conditions associated with waste acceptance of dangerous waste at the IDF are described in the Hanford RCRA permit and document the parameters required by Ecology for waste acceptance and disposal. Requirements include performance data and assessments, the creation and maintenance of a modeling Risk Budget Tool, and updates to the waste analysis plan prior to commencement of operational activities.

Dangerous waste performance information has been included in the DOE-mandated PA required by DOE M 435.1-1 (RPP-RPT-59958). This PA is required for analysis of radioactive constituents, although an assessment of dangerous waste was included to meet the IDF RCRA permit condition. The Risk Budget Tool involves modeling future impacts of the planned IDF waste forms to the vadose zone and groundwater. Results should be compared against performance standards such as drinking water standards. If modeling indicates results within 75% of a performance standard, the permit requires DOE and Ecology to discuss mitigation measures or modified waste acceptance criteria in accordance with IDF Permit Condition III.11.I.5.a.ii (HDWP, 2021). The Risk Budget Tool was developed and provided to Ecology in January 2020 (Vance, 2019).

An update to the waste analysis plan was included in a permit modification request submitted to Ecology in June 2021 (Vance, 2021). This modification request is under review with Ecology. Upon approval, the permit would:

- Allow disposal of mixed waste in Cell 2
- Allow for disposal of secondary waste from WTP vitrification activities
- Remove the option for acceptance of demonstrated bulk vitrification waste
- Add a waste storage pad
- Add a waste treatment pad
  - Treatment would be limited to the immobilization technologies of microencapsulation, macroencapsulation, and sealing.

Additional waste analysis and acceptance permit conditions may be included upon approval of the permit modification request.

Waste Capacity

Plans for IDF include future construction to expand the disposal cells to a length of 501 m (1,645 ft) and width of 410 m (1,345 ft) at ground level, with a depth of 12.8 m (42 ft). The IDF PA assumes that waste loading will comprise 40% of the total available IDF capacity, with the remainder consisting of backfill. This results in a maximum waste disposal capacity of 900,000 m^3 (1,200,000 yd^3) (RPP-RPT-59958). Based on this data, all supplemental LAW treatment technologies would produce waste within the waste disposal capacity of IDF (Table G-3).

System Plan (ORP-11242, *River Protection Project System Plan* [Rev. 9]) waste disposal volumes were estimated for several scenarios that evaluated different volumes split between first LAW and supplemental LAW capacities. Volumes of both vitrified waste and grout for the supplemental LAW volume were presented and used to compare the volumes disposed of onsite in the IDF in the various alternatives (Table G-3). The baseline case, Scenario 1, in the System Plan considers a split of 59% to first LAW and 41 % to supplemental LAW. The presented values are based on this scenario, where the IDF capacity is not exceeded in any cases. Note that one scenario (Scenario 3) presented in the System Plan would exceed the IDF capacity, where over 72% of the treated LAW feed is directed to supplemental treatment.

Table G-3. Estimated Disposal Volumes to the Integrated Disposal Facility

Waste Type	System Plan[a]	LAW Supplemental Treatment Alternatives[b]		
	Scenario 1 m^3 (yd^3)	Grout Onsite m^3 (yd^3)	Grout Offsite m^3 (yd^3)	FBSR m^3 (yd^3)
Immobilized LAW	190,074 (250,097)[c,d]	112,143 (147,557)[e]	112,143 (147,557)[e]	112,143 (147,557)[e]
Grout (primary waste)	0	304,000 (400,000)[f]	0	0
FBSR	0	0	0	202,667 (266,667)[g]
Secondary waste	41,397 (54,469)	24,424 (32,137)	24,424 (32,137)	28,072 (36,936)[h]
Total | % IDF capacity	**231,471 (304,567) | 26%**	**440,567 (579,693) | 49%**	**136,567 (179,693) | 15%**	**342,882 (451,161) | 38%**

[a] ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

[b] Secondary waste volumes calculated based on the assumed ratio of secondary waste projected for the full immobilized LAW inventory in the IDF PA, Table 3-26 (0.218 ratio) (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*).

[c] Taken from Scenario 1 of ORP-11242 [Rev. 9], Table ES-4, assumes 5.51 MT of immobilized LAW per container and a density of 2.58 kg/L (MT/m^3) for the LAW glass.

[d] The LAW supplemental treatment alternative Vitrification 1 would result in equivalent waste disposal volumes as the IDF PA Baseline Case.

[e] Based on the amount of WTP LAW glass, assuming 41% of volume is attributed to supplemental LAW (assumed in Scenario 1 of System Plan [Rev. 9]).

[f] Taken from Scenario 1 of ORP-11242 [Rev. 9], Table ES-4.

[g] Calculated based on the grout volume for supplemental LAW from ORP-11242 [Rev. 9], Table ES-4, and assumes the volume multiplier of waste to grout as 1.8, and of waste to FBSR product as 1.2. (Note that the liquid-to-solid volumetric ratio was conservatively assumed to be 1.2 in transport and disposal calculations related to FBSR. The larger ratio results in a larger FBSR waste volume. The FBSR volumetric ratio assumed in all other analyses discussed in this report was 1.0.)

[h] FBSR assumes a ratio of 0.018 units of secondary waste per unit of primary waste generated (RPP-RPT-63580, *Calculating the Non-Monetary Impact of Operating a Fluidized Bed Steam Reforming Facility*) and added to volume of secondary waste from vitrification.

FBSR = fluidized bed steam reforming.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
PA = performance assessment.
WTP = Waste Treatment and Immobilization Plant.

G.2.2 Energy*Solutions* Disposal Facility (Clive, Utah)

This section presents a summary of the site conditions, disposal facility design, applicable regulations, waste acceptance criteria, and analyses performed in support of the disposal PA (WCS, 2011) for the Energy*Solutions* waste disposal facility in Clive, Utah. This information was collected from multiple sources and presented without further interpretation or reevaluation.

Figure G-2. Location of the Clive Site (base image from Google Earth)

G.2.2.1 Background/General Description

Energy*Solutions* operates a low-level radioactive waste (LLRW) disposal facility west of the Cedar Mountains in Clive, Utah (Figure G-2). Clive is located along Interstate 80, approximately 4.8 km (3 mi) south of the highway in Tooele County.

The facility is approximately 80.5 km (50 mi) east of Wendover, Utah, and approximately 128.7 km (80 mi) west of Salt Lake City, Utah. The facility elevation is approximately 1,303 m (4,275 ft) above mean sea level. The natural topography slopes slightly toward the southwest with approximately 3 m (10 ft) of relief from the northeast corner of the section to the southwest corner of the section. An aerial view of the facility is shown in Figure G-3.

Figure G-3. Aerial View of the Clive Facility

The initial selection of the site location dates back to the late 1970s when DOE and the state of Utah began the cleanup of an abandoned uranium mill site. The Vitro mill site, located in central Salt Lake City, was one of the first sites cleaned up under the DOE Uranium Mill Tailings Remediation Action (UMTRA) Program. DOE investigated 29 sites to identify the safest permanent disposal site for these materials. After 8 years of characterization and evaluation of several sites, DOE selected the Clive site located in Utah's West Desert. The site's remote location, low precipitation, naturally poor groundwater, and low-permeability clay soils were some of the attractive qualities of the area.

From 1984 to 1988, the Vitro tailings were relocated to Clive and placed in an above-ground disposal cell. Since acquiring land adjacent to the Vitro disposal embankment and obtaining a disposal license, the vision of the Energy*Solutions* Clive facility has been to provide a private disposal option for material from cleanups and generators of radioactive waste in separate disposal embankments similar to those used for DOE's Vitro project.

The Clive facility has received waste from cleanup activities carried out across the country, including projects by the EPA, DOE, U.S. Department of Defense (DoD), utilities, and other commercial entities. The initial disposal license was for naturally occurring radioactive material (NORM). Since 1988, the Energy*Solutions* radioactive material license has been amended several times, expanding the types of radioactive materials to include Class A LLRW, in addition to NORM.

The facility is 2.6 km^2 (1 mi^2) in size. The DOE-owned Vitro property occupies approximately 100 acres of the facility. Figure G-4 shows the disposal cells and major man-made and topographic features at the facility. The facility is accessed by both road and rail transportation.

Source: Figure 1 of Energy*Solutions*, 2015, *Bulk Waste Disposal and Treatment Facilities Waste Acceptance Criteri*a, Rev. 10, Energy*Solutions*, Salt Lake City, Utah.

Figure G-4. Clive Facility Disposal Cells and Main Features

Energy*Solutions* began waste disposal activities at the facility in 1988. At present, waste is placed in one of three disposal embankments: Class A West (CAW), mixed waste, or 11e.(2). A fourth embankment, the low-activity radioactive waste (LARW) embankment, located between the mixed waste and 11e.(2) embankments, was closed in October 2005.

On November 26, 2012, the Utah Division of Radiation Control (DRC) approved an amendment to the Energy*Solutions* radioactive material license UT 2300249, "Radioactive Material License Number UT 2300249," to combine the Class A and Class A North embankments into the CAW embankment. The CAW embankment contains the large component disposal area and the Containerized Waste Facility. In the north-central part of the facility, DOE has disposed of the Vitro uranium mill tailings. This area is owned and monitored by the DOE.

Waste disposal cells at the site are permanent, clay-lined cells with composite clay and rock cap designed to perform for a minimum of 500 years.

The Class A Hanford LAW, if disposed of at Clive, would be placed in the CAW embarkment. The disposal volume available at CAW is 2,293,665 m^3 (3 million yd^3). Disposing of all Class A waste at Clive will take from 8% to 15% of the available disposal volume. Clive does not have a limit on the total activity.

Grout waste forms generated by a vendor are assumed to be placed in 8.4 m^3 (11 yd^3) "soft-side" containers. Class A grout will be shipped to Clive using gondola railcars. The details are discussed in Volume II, Appendix H, Section H.7. The grout can be disposed of in the soft-side containers in the bulk waste area of the disposal cell. If the grout is generated at Clive via treatment of radioactive LAW liquids received from Hanford, Clive will then decide on the applicable disposal options.

G.2.2.2 Hydrogeology

The site hydrogeology is described in the 2021 Hydrogeologic Report for the Clive facility (Energy*Solutions*, 2021). This report was developed for the renewal of the Energy*Solutions* Ground Water Quality Discharge Permit, No. UGW450005.

The facility is located in the eastern margin of the Great Salt Lake Desert, part of the Basin and Range Province. This province is characterized by north-south trending mountain ranges with discontinuous alluvium-filled valleys found between the ranges.

The deposits at the facility are the Quaternary-age lacustrine lake bed deposits associated with the former Lake Bonneville. These surficial lacustrine deposits generally comprise low-permeability silty clay.

Beneath the facility, the sediments consist predominantly of interbedded silt, sand, and clay with occasional gravel lenses. The depth of the valley fill beneath the facility is unknown; estimates range from 250 to 3,000 ft below ground surface.

The climate at the facility location is semi-arid with an average precipitation of 8.43 in./year and average pan evaporation of 53.3 in./year based on on-site data collected from 1993 to 2018.

The regional groundwater flow direction is toward the Great Salt Lake to the east-northeast. Groundwater recharge to alluvium-filled valleys in the Basin and Range Province occurs primarily through the alluvial fan deposits along the flanks of the adjoining mountains. Because of the low precipitation and high evapotranspiration, direct infiltration of water into shallow aquifers in the valley floors is negligible.

The four hydrostratigraphic units that are defined beneath the facility are described below.

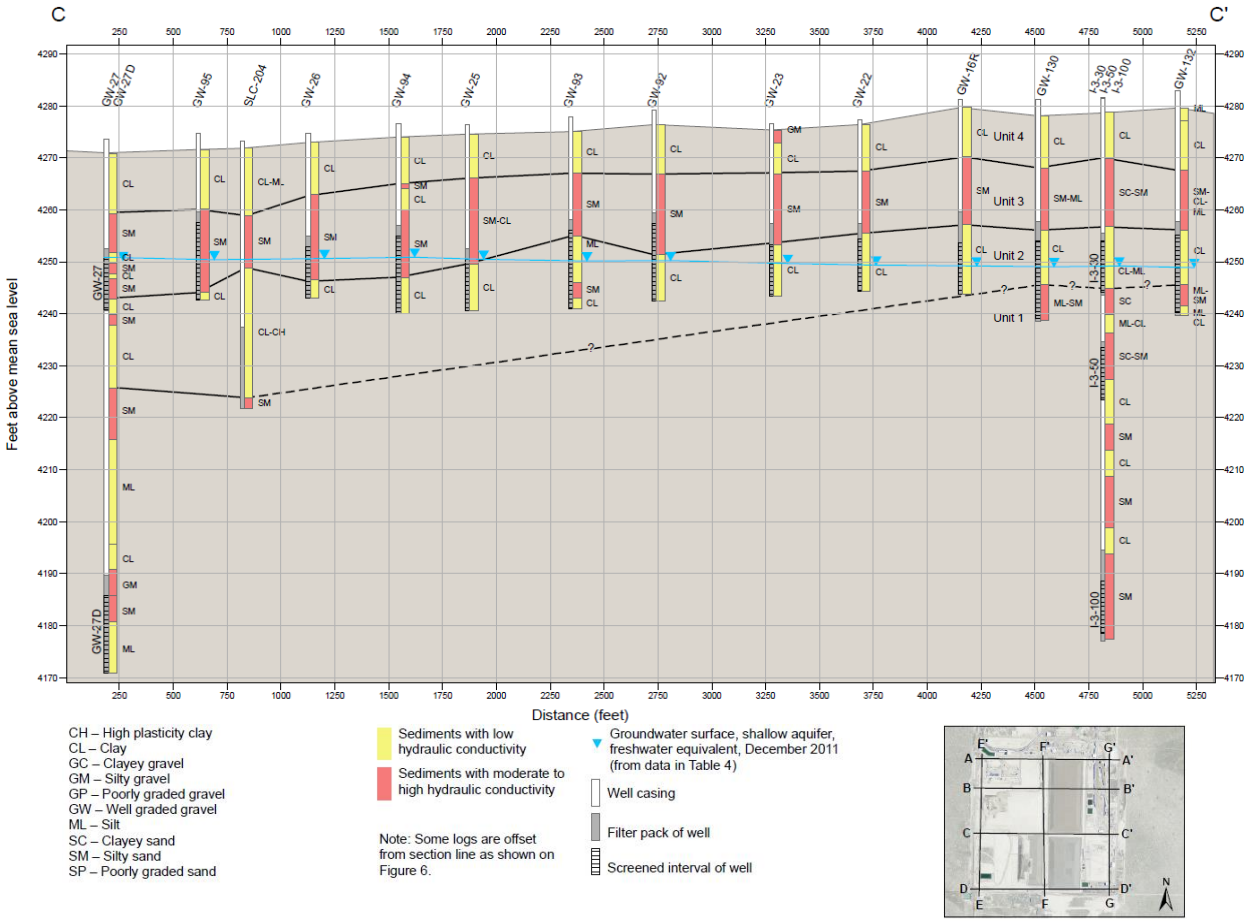
Unit 4: This uppermost unit comprises silt and clay. Unit 4 extends from the ground surface to a depth of 6 to 16.5 ft, averaging approximately 10 ft in thickness. Unit 4 is unsaturated beneath the facility. Unit 4 deposits are used as the liner and radon barrier for waste disposal cells.

Unit 3: Unit 3 underlies Unit 4 and consists predominantly of silty sand, with interbedded silt and clay layers. Unit 3 ranges from 7 to 25 ft in thickness, averaging approximately 15 ft. The lower portion of Unit 3 is saturated beneath much of the western portion of the facility. The unconfined water-bearing zone occurring in Unit 3 (and the upper part of Unit 2) has been designated as the "shallow aquifer".

Unit 2: Unit 2 underlies Unit 3 and typically consists of clay, with occasional silty sand interbeds. Unit 2 ranges in thickness from 9 to 22 ft, averaging 15 ft. The upper part of Unit 2 is saturated beneath the facility, and along with the lower part of Unit 3, comprises the shallow aquifer.

Unit 1: The deepest hydrostratigraphic unit identified beneath the facility, Unit 1 typically consists of silty sand interbedded with clay and silt layers. Few boreholes penetrate this unit, and the thickness has not been determined. Unit 1 is saturated beneath the facility, and contains a locally confined water-bearing zone, designated as the "deep aquifer".

The shallow and deep aquifer are described below. The hydrogeologic cross-section oriented longitudinally is located approximately in the middle of the facility, line C-C' in Figure G-5.



Source: Figure 9 in Energy*Solutions*, 2021, *Revised Hydrogeologic Report Waste Disposal Facility, Clive, Utah*.

Figure G-5. Hydrogeologic Cross-Section C-C′ at Clive

The conceptual representation of the cross-section is shown in Figure G-6.

The isotopic studies conducted to characterize groundwater recharge sources, groundwater age, and groundwater geochemical evolution indicated that the ionic composition of groundwater at the facility was consistent with very slow horizontal flow rates. The groundwater in both aquifers is extremely saline. Groundwater beneath the facility is classified as a Class IV saline groundwater under the state of Utah Groundwater Quality Protection Regulations standards for total dissolved solids (TDS) (exceeding 10,000 mg/L) (*Utah Administrative Code* (UAC) R317-6-3, "Ground Water Classes").

Naturally occurring concentrations of many dissolved constituents (e.g., arsenic, selenium, thallium, radium, and uranium) exceed EPA and Utah State drinking water standards (Mayo and Associates, 1999; Bingham Environmental, 1996; Energy*Solutions*, 2014).

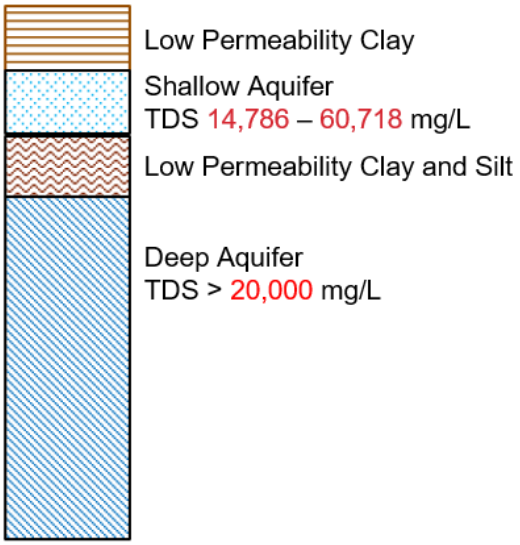


Figure G-6. Conceptual Representation of the Hydrogeologic Cross-Section at Clive

Shallow Unconfined Aquifer

The hydraulic conductivity of the shallow aquifer was estimated from hydraulic tests conducted on 117 wells. The hydraulic gradients were estimated from the hydraulic head data in the monitoring wells. The velocity was calculated for the average gradient using the site-wide geometric mean hydraulic conductivity of 5.96E-04 cm/sec (1.69 ft/day) and porosity of 0.29. Velocities ranged from 3.65E-03 to 9.32E-03 ft/day (0.41 to 1.04 m/year).

Groundwater at the site is extremely saline. Sodium and chloride dominate the major ion composition in the shallow aquifer. The TDS concentration ranges from 14,786 to 60,718 mg/L. The site-wide average of 2018 (or most recently available) TDS data is 40,297 mg/L. The salinity of the water is high because of dissolution of evaporite deposits and concentration of salts due to evapotranspiration.

Deep Confined Aquifer

Less data are available for deep aquifer. Average velocity estimates for horizontal flow in the deep aquifer range from 7.99E-04 to 2.82E-03 ft/day (0.09 to 0.50 m/year), which are similar but slightly slower than estimates for the shallow aquifer.

The deep confined aquifer is separated from the shallow unconfined aquifer by a low permeable portion of Unit 1. The vertical hydraulic conductivity of this portion was measured in the laboratory using soil core samples from deep monitoring (depth interval from 43 to 60 ft). Geometric mean of the vertical conductivity was 2.2E-04 ft/day, which is more than three orders of magnitude lower than the horizontal hydraulic conductivity of the deep and shallow aquifers. The estimated vertical gradient is low. This indicates that the downward flow from the shallow aquifer into the deep aquifer is not significant.

The TDS of the deep aquifer is less than that of the shallow aquifer, but is greater than 20,000 mg/L. The exploratory borehole drilled to a depth of 620 ft in Section 29 did not encounter fresh water (Shrum, 1999). In 2015, Energy*Solutions* sampled deeper groundwater from its well located approximately 3 mi north-northwest of the Clive facility. The well is perforated from 185 to 350 ft. The TDS concentration of the groundwater sample from this interval was 49,800 mg/L.

G.2.2.3 Disposal Facility Design

The design and operation of the Energy*Solutions* disposal site provides a long-term disposal solution with a minimal need for active maintenance after closure. Energy*Solutions* uses an above-ground engineered disposal cell. The design of these cells is patterned after DOE and EPA specifications for the Vitro disposal embankment.

The design of the CAW cell is similar to the design of the existing Class A cell, with a larger footprint. The CAW disposal cell occupies 2,569 × 2,259 ft (approximately 133 acres). The cell is excavated into the native Unit 4 silty clay soil. Waste will be placed above a layer of compacted Unit 4 clayey soils and covered with a layered engineered cover constructed of natural (no man-made) materials. The top slopes of the cell will be finished at a 4.0% grade, with side slopes no steeper than 5:1 (20%). The cover design is engineered to reduce infiltration, prevent erosion, and protect from radionuclide exposure. The landfill design includes both a low-angled top slope and steeper side slope section of the cover. The layers of the CAW top slope cover consist of the following, from bottom to top:

- **Liner**. The cell will be lined with a 0.61 m (2-ft) thick layer of compacted clayey native soil (Unit 4) with a field hydraulic conductivity of 1.0×10^{-6} cm/sec.
- **Waste**. The waste layer will not exceed a final thickness of 23 m (75.3 ft) above the top of the clay bottom liner. The height of waste at the shoulder of the top slope (the contact between the top slope and side slope) will be approximately 11.4 m (37.6 ft).
- **Radon barrier**. The top slope cover design contains an upper radon barrier consisting of 0.3 m (12 in.) of compacted clay with a maximum hydraulic conductivity of 5×10^{-8} cm/sec and a lower radon barrier consisting of 0.3 m (12 in.) of compacted clay with a hydraulic conductivity of 1×10^{-6} cm/sec.
- **Filter zone (lower)**. The 0.15 m (6 in.) of Type B filter material will be placed above the radon barrier in the top slope cover. This filter material ranges in size from <0.187 to 1.5 in. The Type B size gradation corresponds to a coarse sand and fine gravel mix.
- **Sacrificial soil (frost protection layer)**. A 0.3 m (12-in.) layer consisting of a mixture of silty sand and gravel will be placed above the lower filter zone to protect the lower layers of the cover from freeze/thaw effects. The sacrificial soil material ranges in size from <0.003 to 0.75 in.
- **Filter zone (upper)**. The 0.15 m (6 in.) of Type A filter material will be placed above the sacrificial soil in the top slope cover. The Type A filter material ranges in size from <0.003 to 6.0 in. The Type A size gradation corresponds to a poorly sorted mixture of coarse sand to coarse gravel and cobble.
- **Rip rap cobbles**. Approximately 0.45 m (18 in.) of Type B rip rap will be placed on the top slopes, above the upper (Type A) filter zone. The Type B rip rap used on the top slopes ranges in size from <0.003 to 4.5 in., with a nominal diameter of approximately 1.25 to 2 in.

The design for the side slope is similar to the top slope, except for the thickness of the waste layer and the material used in the rip rap layer.

- **Waste**. The thickness of waste will range from zero at the edge of the cell to 11.4 m (37.6 ft) at the shoulder, for an average waste height of 5.7 m (18.8 ft) [(0+37.6)/2].
- **Rip rap cobbles**. Approximately 0.45 m (18 in.) of Type A rip rap will be placed on the side slopes above the Type A filter zone. The Type A rip rap ranges in size from <0.003 to 16 in. (equivalent to coarse gravel to boulders) with a nominal diameter of 12 in.

G.2.2.4 Key Regulatory Requirements

The applicable federal agency that regulates disposal of LLRW at the Clive facility is the NRC. The regulations (10 CFR 61, and Utah regulation R313-25-9, "Technical Analyses") indicate the need to evaluate performance with respect to members of the public and inadvertent human intruders.

The state of Utah has been authorized by the NRC as an Agreement State and has regulatory authority over the Clive facility. The DRC was previously the state agency with oversight over the facility. In 2015, the state of Utah combined the DRC with the Division of Solid and Hazardous Waste to create the Division of Waste Management and Radiation Control (DWMRC). The DWMRC currently has regulatory oversight over the Clive facility.

Energy*Solutions* is permitted by the state of Utah to receive Class A LLW under UAC R313-25, "License Requirements for Land Disposal of Radioactive Waste." The wastes that are received must be classified in accordance with the UAC R313-15-1009, "Classification and Characteristics of Low-Level Radioactive Waste." The classification requirements in UAC R313-15-1009 reflect those outlined in 10 CFR 61.55, but include additional references to radium-226 (^{226}Ra).

Subpart C of 10 CFR 61 specifies the performance objectives for the near-surface LLW disposal facilities – protection of general population and inadvertent intruders. The near-surface disposal is defined as disposal in or within the upper 30 m (100 ft) of the earth's surface (10 CFR 61.2).

10 CFR 61.41, Protection of the General Population from Releases of Radioactivity
Concentrations of radioactive material that may be released to the general environment in groundwater, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 mrem (0.25 mSv) to the whole body, 75 mrem (0.75 mSv) to the thyroid, and 25 mrem (0.25 mSv) to any other organ of any member of the public. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable (ALARA).

10 CFR 61.42, Protection of Individuals from Inadvertent Intrusion
Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste at any time after active institutional controls over the disposal site are removed.

No dose limit is specified in 10 CFR 61 for the inadvertent intruder. However, since 10 CFR 61 has been issued, the standard used by NRC and others for LLW disposal licensing has been an annual dose of 500 mrem. The 500 mrem-in-a-year standard is also used in the DOE waste determinations implementing the 10 CFR 61 performance objectives (NUREG-1854, *NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations – Draft Report for Interim Us*e), and as part of the license termination rule dose standard for intruders (10 CFR 20.1403, "Criteria for License Termination under Restricted Conditions").

In addition, groundwater protection levels (GWPL) must be adhered to, as outlined in the site's Ground Water Quality Discharge Permit (UWQB, 2010). The GWPLs are numerical standards that are set by Utah Department of Environmental Quality (UDEQ) in the groundwater quality discharge permit (UWQB, 2009). Groundwater in the vicinity of the site is defined as Class IV, saline groundwater (UWQB, 2009), and GWPLs for existing wells were determined by UDEQ according to administrative rules for Class IV saline aquifers. GWPLs were set at the greater of either the Ground Water Quality Standard (GWQS) or the upper boundary of the background concentration. The upper boundary of the background concentration was calculated as the mean concentration plus two standard deviations for each constituent in each individual well, based on Clive facility groundwater quality samples.

Table 1A of the permit lists "universal" GWPLs that apply to all LARW, Class A, CAW, and Evaporation Pond wells, and Table 1B of the permit lists GWPL exceptions that apply to specific LARW, Class A, CAW, and Evaporation Pond wells.

G.2.2.5 Waste Acceptance Criteria

The type, form, and quantity of LLRW, NORM, 11e.(2) byproduct material, and mixed waste that can be treated and disposed of at the Clive facility is defined in various licenses and permits. The licenses issued to Energy*Solutions* by the Utah DWMRC applicable to LLRW and mixed waste are:

Table G-4. Long-Lived Radionuclide Concentration Limits

Radionuclide	Ci/m³	nCi/g
^{14}C	8	-
^{14}C (act)	80	-
^{59}Ni (act)	220	-
^{94}Nb (act)	0.2	-
^{99}Tc	3	-
^{129}I	0.08	-
Alpha-emitting transuranics >5-year half-life	-	100
^{241}Pu	-	3,500
^{242}Cm	-	20,000
^{226}Ra	-	100

Source: Table I of UAC R313-15-1009, "Classification and Characteristics of Low-Level Radioactive Waste," *Utah Administrative Code*, as amended.

- An Agreement State radioactive material license (UT 2300249). This license authorizes Energy*Solutions* to receive Class A LLRW, NORM, and naturally occurring and accelerator-produced radioactive material (NARM) waste.
- A state-issued Part B Permit (EPA ID Number UTD982598898) to treat and dispose of hazardous waste that is also contaminated with LLRW, NORM, or NARM wastes (mixed waste).
- An Agreement State radioactive material license (UT 2300478) for 11e.(2) byproduct material (as defined by the *Atomic Energy Act of 1954* [AEA]).

The determination of waste class involves two considerations. First, consideration must be given to specific long-lived radionuclides listed in Table I of UAC R313-15-1009 (reproduced as Table G-4). Second, consideration must be given to specific short-lived radionuclides listed in Table II of UAC R313-15-1009 (reproduced as Table G-5). Note that the Clive waste acceptance criteria in Table G-4 and Table G-5 are identical to the WCS waste acceptance criteria.

- When the waste does not contain any radionuclides listed in either Table I or II, the waste is Class A.
- When the concentration does not exceed 0.1 times the value in Table I, the waste is Class A. For wastes containing mixtures of radionuclides listed in Table I, the total concentration is determined by the sum of fractions rule (details are discussed in Volume II, Appendix H, Section H.6).
- When the waste does not contain any of the radionuclides listed in Table I, classification is determined based on the concentrations shown in Table II. When the concentration does not exceed the value in Column 1 of Table II, the waste is Class A. For wastes containing mixtures of the radionuclides listed in Table II, the total concentration is determined by the sum of fractions rule (details are discussed in Volume II, Appendix H, Section H.6).

Table G-5. Short-Lived Radionuclide Concentration Limits

Radionuclide	Column 1 Ci/m³	Column 2 Ci/m³	Column 3 Ci/m³
Total of all radionuclides <5 year half-life	700	*	*
^{3}H	40	*	*
^{60}Co	700	*	*
^{63}Ni	3.5	70	700
^{63}Ni (act)	35	700	7,000
^{90}Sr	0.04	150	7,000
^{137}Cs	1	44	4,600

Source: Table II of UAC R313-15-1009, "Classification and Characteristics of Low-Level Radioactive Waste," *Utah Administrative Code*, as amended.

* There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes. These wastes shall be Class B unless the concentrations of other radionuclides in Table II determine the waste to be Class C independent of these radionuclides.

In addition to waste acceptance criteria, ALARA criteria are applied to minimize worker exposures. The ALARA criteria are not a license condition but are used as the primary distinction between waste that is acceptable for direct disposal at the Bulk Waste Facility and Containerized Waste Facility.

The ALARA criteria summarized in Table G-6 define allowable external contact dose rates and loose surface contamination limits for waste managed at the Bulk Waste Facility.

Table G-6. ALARA Criteria for External Contact Dose Rate and Surface Contamination Limits

External Contact Dose Rate	Removable Surface Contamination On Exterior Surfaces of Debris
< 200 mR/hr on manifested container	< 500 dpm α/100 cm²
< 500 mR/hr on external, accessible surfaces of waste in container	< 50,000 dpm β,γ/100 cm²
< 80 mR/hr on contact of unshielded container with resin	

Source: Energy*Solutions*, 2015, *Bulk Waste Disposal and Treatment Facilities Waste Acceptance Criteria*, Rev. 10, Energy*Solutions*, Salt Lake City, Utah.

G.2.2.6 Disposal Performance Evaluation of Class A West (CAW) Disposal Cell

On May 2, 2011, Energy*Solutions* submitted an amendment to Radioactive Material License UT 2300249 to combine the Class A and Class A North embankments into the CAW embankment. The design and operation of the proposed CAW embankment were substantially similar to those already approved for use in the Class A North and Class A disposal embankments. However, the most recent site data and PA were included in the amendment request. The DRC conducted the review of the amendment request and documented the results of this review in DRC-2012-003582, *Safety Evaluation Report* (SER). The main conclusion was that all of the applicable requirements of UAC R313-25 were satisfied. On November 26, 2012, DRC approved the amendment request.

The following description summarizes how the applicable requirements of UAC R313-25 were met. Note that the protection provided to members of the general public is largely unchanged from what the DRC approved following its review of the 2005 License Renewal Application (Envirocare, 2005).

UAC R313-25-20, Protection of the General Population from Releases of Radioactivity

This requirement sets the dose limits to the general population due to the exposure to the radioactive materials released in groundwater, surface water, air, soil, plants, or animals. Clive is a remote and environmentally inhospitable area for human habitation. Human activity at Clive has historically been very limited, due largely to the lack of potable water, or even water suitable for irrigation. None of the exposure pathways at the site are viable as explained below. However, the groundwater pathway was analyzed in great detail to provide evidence that GWPLs in the compliance monitoring well are below the limits outlined in the site's Ground Water Quality Discharge Permit (UWQB, 2010). The potential groundwater impacts from the CAW embankment were evaluated in Whetstone Associates (2011).

Air Pathway

After final placement of the waste and closure of the disposal embankment, the facility design prevents any further migration of radioactivity through the air pathway because all waste will be beneath a thick earthen cover. Radon releases will be negligible because the cover design includes a clay radon barrier designed to limit the surface radon flux to less than 20 pCi/m^2, resulting in potential radon exposures well within limits. The design is based on the disposal of uranium mill tailings, which are higher in ^{226}Ra than the Class A waste.

Soil Pathway

The soil pathway involves the exposure of the public to contaminated soil from the facility. If an exposure occurred, doses could result from external radiation or ingestion of soil on dirty hands. The primary site characteristics that prevent the likelihood of such exposures during operations is the site's remote location, low population density in the site vicinity, and lack of natural resources to provide for population expansion. The design of the embankment also contributes to minimizing exposures to contaminated soil by members of the public.

After closure of the embankment, all contaminated soil will be covered in the disposal cells. The cover system includes a surface layer of riprap to protect against erosion and human intrusion. Beneath the riprap, the cover system has a drainage layer and a clay radon barrier. The thickness of the cover system prevents penetration of the waste by roots or burrowing animals. No contaminated soil material is expected to rise to the ground surface or be otherwise removed from the disposal cell.

Surface Water Pathway

Due mainly to the natural site characteristics, no radioactive releases are expected through the surface water pathway. The annual precipitation is low and evaporation is high. No permanent surface water bodies are on the site. The nearest stream channel is about 2 mi east of the facility. In addition, the site is far from populated areas. Surface water from precipitation is directed away from the waste disposal embankment by drainage ditches and berms. The embankment design features also minimize the potential for releases by the surface water pathway. After precipitation events, the drainage ditches around the disposal areas will divert runoff to areas away from the disposal cells.

Plant Pathway

Exposures via the plant uptake pathway are not expected. Insufficient water exists at the site to produce food crops. In addition, saline soils present at the site limit the number and type of plant species that can tolerate such conditions. Few deep-rooted native plants are in the site vicinity and relatively few plants of any kind are predicted to become established on the rock riprap-capped CAW embankment cover system at and following closure of the embankment. Design features of the facility also help prevent exposures via the plant uptake pathway. A thick earthen cover will be placed over the disposal cells to make the waste inaccessible to plant roots after closure of the facility.

The possibility of native plants extending their roots into the waste is prevented by the configuration of the earthen cover with the lower Type B filter functioning as a capillary break, with minimal moisture storage to attract or even support plant roots.

Burrowing Animal Pathway

The burrowing animal pathway is not expected to result in any exposures to humans. Burrowing animals at the site include jackrabbits, mice, foxes, and ants. The first deterrent to burrowing animals is the riprap erosion barrier. While this may be only partially effective in deterring animals, the primary protective barrier is the clay radon barrier. The burrowing species at the site are not known to dig to such a depth that their burrows could penetrate through the entire cover and into the waste.

Groundwater Pathway

The groundwater protection criteria are based on an annual dose of 4 mrem to an individual drinking groundwater. The primary site characteristics that prevent public exposures via the groundwater pathway are the very poor groundwater quality at the site, low population density, and relatively slow groundwater flow velocities. No domestic water use occurs within 10 km of the facility.

The groundwater is not potable because of its very high concentration of salts. The TDS in the shallow and deep aquifer exceed 20,000 mg/L. Per the EPA secondary drinking water regulations, 500 mg/L is the recommended maximum amount of TDS for drinking water. Any measurement higher than 1,000 mg/L is an unsafe level of TDS. Additionally, several embankment design features provide protection of the public from exposure via the groundwater pathway. The cover system to be placed over the disposal waste allows very little water to flow into the disposed waste. This limits the contamination of the groundwater by minimizing the contact of water with the waste. Another design feature of the disposal embankment is the bottom clay liner below the disposed waste. The clay absorbs many of the radionuclides and slows their potential release from the cell and subsequent transport to the water table. Even though the groundwater is not potable, potential doses to the public from groundwater were calculated and met all applicable limits.

UAC R313-25-21, Protection of Individuals from Inadvertent Intrusion

Utah regulations require special provisions to protect inadvertent intruders from disposed LLRW only for Class C LLRW. Since only Class A waste will be disposed of in the proposed CAW embankment, no special intruder barrier, as defined by Utah regulations, is required. In a more general sense, however, intruder protection is required by the performance objective stated in UAC R313-25-20, “Protection of the General Population from Releases of Radioactivity.” The intruder protection requirement is satisfied by the facility remoteness from large population centers, lack of resources at the site, provision of a cover system to separate the waste from the atmosphere, construction and maintenance of physical access barriers at the closed facility, maintenance of access controls at the closed facility, and placement of monuments denoting the locations of embankment boundaries. The embankment cover system provides the long-term barrier to inadvertent intrusion, with 1.1 m (3.5) ft of rock layers, 0.61 m (2 ft) of clay, and 0.3 m (1 ft) of noncontaminated native soil as a “temporary cover” above the waste.

The NRC evaluated the long-term hazards of LLRW disposal in its draft and final environmental impact statements of the regulation of LLRW disposal (NUREG/CR-4370, *Update of Part 61 – Impacts Analysis Methodology*). Radiation hazards associated with Class A waste are such that: should intrusion into disposed waste occur following the 100-year institutional control period, doses were projected to be within acceptable limits.

Groundwater Protection Requirements

Groundwater protection requirements place limits on the individual radionuclide concentrations in the groundwater at the compliance monitoring well. The radionuclide concentration limits must not be exceeded for at least 500 years following closure of the facility. An extensive analysis of groundwater pathway was performed in support of the license amendment request. This analysis is documented in Whetstone Associates (2011).

Fate and transport modeling of a similar nature was performed previously for the Class A cell, LARW cell, 11e.(2) cell, and mixed waste cell at the Energy*Solutions* Clive facility. This modeling was based on site-specific parameters, where available, or conservative assumptions where no site-specific data existed. Over time, with more data collected for the site, these models were refined and updated to provide more accurate yet environmentally conservative estimates of the leaching, transport, and arrival of constituents at the compliance monitoring well. The methodology used in the modeling was initially described in a two-volume comprehensive modeling report for the LARW cell (Adrian Brown Consultants, 1997).

The following description is based on information provided in Whetstone Associates (2011). Figure G-7 shows the conceptual model considered in the analysis.

Inventory

The CAW disposal cell will contain LLRW and metals for permanent disposal. The Whetstone Associates (2011) analysis evaluated a total of 260 radionuclides and 13 metals.

The refinements in radionuclide inventory, half-lives, and sorption coefficients (K_d) values for the Class A radionuclides were incorporated into this analysis. The analysis used the most up-to-date Class A nuclide inventory approved by DRC at the time.

The waste concentrations for each isotope were initially developed in 2000 from data supplied by the Manifest Information Management System (MIMS), a database managed by DOE that summarizes national LLRW disposal information. The list of radioisotopes established from the MIMS database was then classified by UAC R313-15-1009 and their respective maximum Class A concentrations determined. If not listed on Table I or Table II (reproduced as Table G-4 and Table G-5), the radioisotope is Class A in accordance with UAC R313-15-1009(2)(f). In these cases, the waste source term in the model was set at the specific activity. The waste source term concentrations used in the analysis were identical to those used in previous modeling of the Class A cell (Whetstone Associates, 2000) with a few exceptions.

The radionuclide concentrations in pCi/g were converted to Ci/m^3 using the waste bulk density of 1.8. A value of 1.8 gm/cm^3 was used for the bulk density of the waste. This value is consistent with previous modeling and the range of density determined by Energy*Solutions* (1.75 to 1.80 gm/cm^3) for the compacted, in-place waste.

The GWPLs are specified in the site's Ground Water Quality Discharge Permit (UWQB, 2010) only for a subset of evaluated 260 radionuclides. Groundwater standards for the radionuclides that are not specifically listed in the permit were developed from the following main sources:

- Maximum contaminant levels (MCL) and secondary MCLs (SMCL) in drinking water established by UDEQ and the EPA.

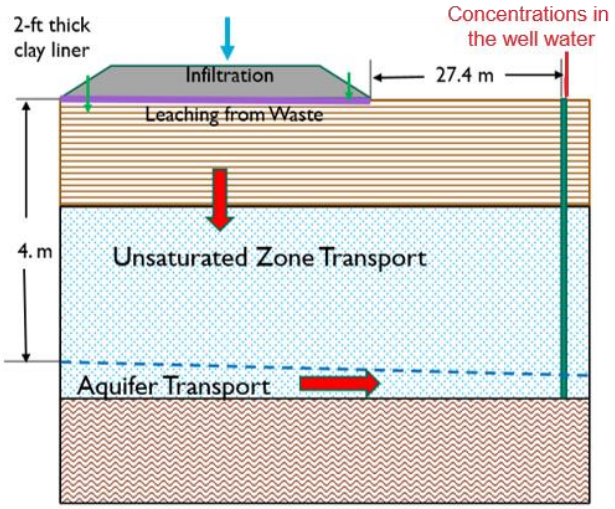


Figure G-7. Conceptual Model Considered in the Groundwater Protection Analysis

- Proposed drinking water standards for alpha emitters, as published in 56 FR 33078, "40 CFR Parts 141,142, National Primary Drinking Water Regulations; Radionuclides," Appendix C, Alpha Emitters.
- Proposed drinking water standards for beta emitters, as published in the 56 FR 33120, "40 CFR Parts 141,142, National Primary Drinking Water Regulations; Radionuclides," Appendix B, Beta Particle and Photon Emitters.

The Whetstone Associates (2011) analysis evaluated 260 radionuclides. However, 92 radionuclides and seven surrogates were explicitly modeled. Radionuclides having very short half-lives and/or very high sorption coefficients (K_d) were modeled using one of the seven surrogate isotopes.

The non-radiological constituents evaluated in the analysis and their GWPLs are listed in Table G-7.

Table G-7. Groundwater Protection Levels for Non-Radiological Constituents

Parameter	GWPL (mg/l)	GWPL (kg/m^3)
Arsenic	0.05	5.00E-05
Barium	2	2.00E-03
Beryllium	0.004	4.00E-06
Cadmium	0.005	5.00E-06
Chromium	0.1	1.00E-04
Copper	1.3	1.30E-03
Lead	0.015	1.50E-05
Mercury	0.002	2.00E-06
Molybdenum	0.04	4.00E-05
Nickel	0.1	1.00E-04
Selenium	0.05	5.00E-05
Silver	0.1	1.00E-04
Zinc	5	5.00E-03

GWPL = groundwater protection level.

Infiltration through the Cover

The EPA Hydrologic Evaluation of Landfill Performance (HELP) computer model was used to evaluate the infiltration rate of water through the cover. The annual average precipitation used as an input in the HELP model was 8.53 in./year based on the site data from the 17-year record. The HELP infiltration modeling results indicate that 0.0937 in./year (0.238 cm/year) infiltration would occur through the CAW cell top slope, while 0.132 in./year (0.335 cm/year) would infiltrate through the side slope with a 6-in. thick Type B filter. Based on these HELP-generated infiltration rates, the UNSAT-H model, a one-dimensional finite difference numerical model, was selected to evaluate the migration of water in the unsaturated soils at the site. The UNSAT-H model predicted that moisture contents would stabilize at 0.057 in the waste and 0.043 in the native soil below the top slope, and at 0.0599 and 0.045 in the waste and native soil below the side slope (which are comparable to those originally modeled for the Class A Cell).

Contaminant Release from the Waste Form

In defining the contaminant release rate, the clay cover is assumed to immediately degrade and the infiltration water moves through the cover instantaneously. No credit was taken for the container life and for the time required for the infiltration water to percolate through the cover. The infiltration rates and moisture contents of the waste were used to calculate the constant release rate of the contaminants from the waste form as:

$$L = \frac{q_{in}}{d\theta\left(1 + \frac{\rho K_d}{\theta}\right)} \quad \text{(G-1)}$$

where L = fractional annual contaminant release rate (yr^{-1})
q_{in} = water infiltration rate (m/yr)
θ = volumetric moisture content of waste
d = waste layer thickness (meters)
ρ = waste density (g/cm^3)
K_d = waste distribution coefficient (ml/g)

In reality, a significant delay will occur for the time required to wet the cover and the waste, and for moisture to travel through the cell cover, waste, and liner. The moisture content in the waste at the time of cell closure may also be well below the levels assumed at the start of the closed cell modeling.

The K_d values used in modeling at the Energy*Solutions* site have evolved over time, as radionuclide inventories changed and more information was obtained from the literature and from site-specific K_d testing. The modeling performed for the CAW cell incorporates the current approved K_d values for the site.

The modeling preferentially uses (1) approved site-specific K_d values, (2) the lowest measured soil K_d values published in the literature, and (3) published K_d values calculated from the soil:plant ratio. Approved site-specific K_d values were available for cesium, cobalt, ^{14}C, ^{129}I, ^{237}Np, ^{99}Tc, uranium, and zinc. The most conservative (lowest) K_d values found in the literature were used for nuclides that did not have site-specific K_d values.

Contaminant Transport from the Waste Form to the Water Table

The contaminants released from the waste are transported first through the unsaturated zone beneath the bottom of the waste to the water table. The unsaturated zone includes the 2-ft thick clay liner below the waste bottom and excludes the capillary fringe at the water table. The resulting unsaturated zone thickness is 13.36 ft. The flow through the unsaturated zone was modeled with UNSAT-H.

The contaminant transport was modeled with computer code PATHRAE. PATHRAE solves the advection/dispersion equation, includes aquifer diffusion, assumes that diffusion is Fickian, allows for retardation of contaminants using retardation coefficient (K_d), and includes radioactive decay.

PATHRAE is limited to solving the contaminant transport equation in one homogeneous medium. The characteristics of individual units in the unsaturated zone were converted to a single equivalent porous medium. The unsaturated zone velocities calculated for the equivalent porous media (liner and silty sand) underlying the top slope and side slope simulations are 0.418 and 0.302 cm/year. The dispersivity in the unsaturated zone transport model was set to 0.1 m.

None of the 99 radionuclides exceeded the GWPLs at the water table within 500 years in the top slope and side slope models. Sixteen out of 99 radionuclides exceeded the GWPLs at the water table at some time after 500 years. Most of the radionuclides did not exceed GWPLs at the water table due to a high K_d value, low starting concentration, or short half-life.

The top slope and side slope model results indicated that none of the metals modeled would arrive or exceed GWPLs at the water within 200 years. The metal transport in the aquifer was not modeled because all GWPLs were met at the water table.

Contaminant Transport in the Shallow Aquifer

The transport of 16 radionuclides in the shallow aquifer was modeled with PATHRAE to determine the radionuclide concentrations at a compliance well.

The hydraulic conductivity of the shallow aquifer was 7.53×10^{-4} cm/sec, based on the 90% upper confidence level for the Unit 3 sand calculated from 118 slug tests conducted sitewide. The permit for the existing Class A and Class A North cells gives a maximum allowable hydraulic gradient 1.0×10^{-3} ft/ft for the shallow aquifer beneath the cells. Previous and current modeling was based on this hydraulic gradient. The assumed aquifer porosity was 0.29. The resulting velocity in the shallow aquifer was 0.819 m/year.

The horizontal distance was modeled as the distance from the edge of the waste to the nearest compliance monitoring well. The side slope modeling used a horizontal distance of 90 ft (27.4 m).

The distance from the compliance well to the edge of the waste under the top slope was modeled using the side slope length (188 ft) plus the distance from the side slope to the well (90 ft) for a total distance of 278 ft from the waste to the compliance monitoring well. The top slope modeling used this 278 ft (84.7 m) horizontal transport distance.

The PATHRAE fate and transport modeling for the top slope (0.238 cm/year infiltration case) indicates that all radionuclides modeled would remain below the GWPLs for at least 500 years at a compliance well located 278 ft from the edge of the top slope waste, provided that the concentrations of two radionuclides, ^{247}Bk and ^{36}Cl, are received in limited concentrations of 1.92 and 73,900 pCi/g, respectively. All other modeled constituents would meet the groundwater standard if placed in the top slope area at Class A limits.

The PATHRAE fate and transport modeling for the side slope with a 6-in. thick Type B filter (0.335 cm/year infiltration case) indicates that all radionuclides modeled would remain below the GWPLs for at least 500 years at a compliance well located 90 ft from the edge of the waste, provided that ^{36}Cl is received in limited concentrations of 106,000,000 pCi/g. All other modeled constituents would meet the groundwater standard if placed under the side slope at Class A limits.

All 13 metals could be placed in the top slope or side slope at the maximum possible concentration based on density, and would meet GWPLs at the water table and, by extension, at a compliance well located 90 ft from the edge of the waste for the 200-year compliance period established for heavy metals.

The analysis demonstrated that reductions in side slope infiltration eliminates the necessity to limit waste disposal concentrations beneath the CAW side slope for ^{36}Al, ^{247}Bk, ^{41}Ca, ^{249}Cf, ^{250}Cf, ^{36}Cl, ^{187}Re, ^{157}Tb, and ^{158}Tb, as originally modeled in 2000.

G.2.2.7 Disposal Performance Evaluation of a Proposed Depleted Uranium Cell

A separate PA analysis was performed for the proposed disposal of the depleted uranium (DU) in a designated DU disposal cell at the Clive facility. This analysis is documented in (Neptune, 2021). The PA is probabilistic and goes beyond the 500 years because DU reaches peak activity at 2.1 Myr. Even though this analysis was done for a different inventory than the one that will be disposed of at the CAW disposal cell, the analysis provides additional confidence in the performance of the Clive facility. The most important assumptions and conclusions of the DU PA are summarized below.

The Clive DU PA model was implemented quantitatively for 10,000 years and has run additional simulations for 2.1 Myr.

In the saturated zone (aquifer), contaminants are transported laterally to a hypothetical monitoring well located about 27 m (90 ft) from the edge of the interior of the cell. The distance to the well from the DU waste is about 73 m (240 ft).

The PA considers both the groundwater pathway and the air pathway. Radionuclides are transported via diffusion in both water and air phases within the cover system. Once radionuclides reach the ground surface at the top of the engineered cover, they are subject to suspension into the atmosphere and dispersion to the surrounding landscape. Atmospheric transport of gases (^{222}Rn) and contaminants sorbed to suspended particles is modeled using a standard modeling platform approved by EPA, AERMOD. The results of this model are used to calculate contributions of airborne radionuclides to dose, and the uranium toxicity hazard is evaluated.

The Clive DU PA evaluated the doses to a member of the general public and to inadvertent intruders.

For the Clive facility, based on the NRC definitions, ranch hands, hunters, and off-highway vehicle riders are expected to engage in activities both on and off the site. These receptors fit the NRC definition of inadvertent intrusion.

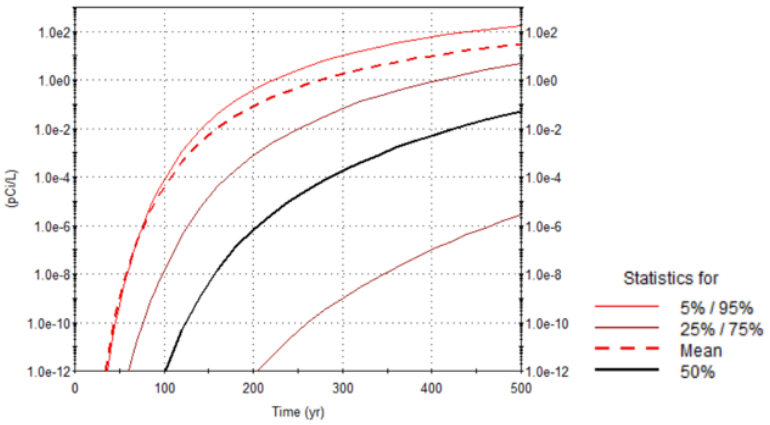
The receptors that are located at specific off-site locations fit the NRC definition of member of the public. There are specific points of exposure within the vicinity of the Clive facility where individuals might be exposed. About 12 km (8 mi) to the west, off-highway vehicle riders use the Knolls Recreation Area. Interstate 80 and a railroad are located to the north, with an associated rest area on the highway. Closer to the Clive facility, the Utah Test and Training Range access road is used on occasion.

The doses to members of the public and inadvertent intruders were calculated within a 10,000-year compliance period. The doses are compared to a performance criterion of 25 mrem in a year for a member of the public, and 500 mrem in a year for an inadvertent intruder.

After that time, the modeling focus turns to long-term, or "deep time" scenarios. Peak activity of the waste occurs when the progeny of the principal parent, ^{238}U reaches secular equilibrium. This occurs at roughly 2.1 Myr from the time of isotopic separation, and the Clive DU PA evaluated the potential future of the site in this context. The evaluation takes into account the likely possibility of future deep lakes in the Bonneville Basin and eolian (i.e., wind-borne) deposition of dust/particles. As each lake returns, estimates are made of the radionuclide concentrations in the lake and in the sediments surrounding and subsuming the site.

The probabilistic PA results are reported in terms of the mean, median, and 95th percentiles of the dose at 10,000 years for the 10,000 realizations. The peak mean dose is sometimes of interest for comparison with performance objectives, and in this model, the peak mean dose occurs at or near 10 kyr. In effect, 10 kyr is the worst-case year in terms of dose. Under these circumstances, the 95th percentile is analogous to the 95% upper confidence interval of the mean at 10 kyr that is commonly used to represent reasonable maximum exposure in the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) risk assessments.

Compliance with the performance objectives for the inadvertent intruder dose of 500 mrem/year and for a member of the public of 25 mrem/year is clearly established for all types of potential future receptors. None of the 95th percentile dose estimates for these receptors exceeds 1 mrem/year, and all of the peak mean dose estimates are at or below 0.1 mrem/year. Sensitivity analyses indicated that receptor doses are dominated by radon inhalation for the air pathway and groundwater concentrations of ^{99}Tc for the groundwater pathway. Figure G-8 shows the ^{99}Tc concentrations in the compliance well for the different percentiles based on 1,000 realizations.



Source: Figure 6 of Neptune (2021).

Figure G-8. Statistics of Technetium-99 Concentrations in the Compliance Well (1,000 realizations)

The ^{99}Tc inventory considered in this analysis was 16,000 Ci. The resulting ^{99}Tc concentration in the compliance well leads to a small dose (below 0.1 mrem/year) even when an extended compliance period was considered. The total ^{99}Tc inventory in the Hanford LAW is only 11% larger (18,000 Ci); therefore, the dose is also expected to be small. The Clive DU PA results suggest that the below-grade disposal configuration can be used to dispose of the quantities of DU waste included in the analysis in a manner adequately protective of human health and the environment.

G.2.2.8 Confidence in Successful Disposal

This section summarizes the aspects that contribute to the confidence in the successful disposal at the Clive site.

The site natural conditions ensure safe permanent disposal of LLRW

In the 1970s, DOE investigated 29 sites to identify the safest permanent disposal site for uranium tailings. After 8 years of characterization and evaluation of several sites, DOE selected the Clive site. The site's remote location, low precipitation, naturally poor groundwater, and low-permeability clay soils make this site well suited for the safe permanent disposal of LLRW.

The initial site application and the subsequent amendments went through a rigorous review process, including public hearing and comments, and were approved

The initial Energy*Solutions* disposal license was for NORM. Since 1988, the Energy*Solutions* radioactive material license has been amended several times. The 2011 license amendment request for CAW, a disposal area that contains a federal disposal cell, required updating the scientific and engineering analyses to reflect current practices and state-of-the-art science and engineering procedures.

The CAW license amendment request was approved by the DRC in 2012. The DRC reviews a license application to determine the extent to which each applicable regulatory requirement is satisfied and to ensure that particular licensing actions are justifiable under provisions of the regulations.
The requirements and criteria for licensing commercial LLRW disposal facilities are included in UAC R313-25. UAC R313-25 address such topics as:

- Performance objectives
- Site suitability requirements
- Facility design, construction, operating, closure, and post-closure requirements
- Waste characteristic requirements
- Environmental monitoring requirements
- Financial assurance and financial qualifications requirements
- Administrative requirements.

The license amendment process includes the following steps:

- Review license amendment request
- Prepare interrogatories as necessary to resolve issues not adequately addressed in the amendment request
- Review interrogatory responses, ensuring that all required information is included in either the initial submittal or responses to interrogatories
- Prepare draft SER and draft revised license conditions
- Publicize the Director's decision to amend the license
- Conduct public hearings and receive public comment
- Prepare public participation document
- Prepare final SER and final license revisions.

Depleted Uranium Performance Assessment

A separate PA analysis was performed for the proposed disposal of the DU in a designated DU disposal cell at the Clive facility. The PA is probabilistic and goes far beyond the 500 years because DU reaches peak activity at 2.1 Myr. Even though this analysis was done for a different inventory than the one that will be disposed of at the CAW disposal cell, the analysis provides an additional confidence in the performance of the Clive facility.

Operational Experience

Energy*Solutions* has over 34 years of experience operating the Clive facility. The NORM waste disposal operations at the Clive facility began in 1988. LLRW disposal operations began in 1991. Mixed waste disposal operations have been conducted since 1992.

The Clive facility has received waste from cleanup activities carried out across the country, including projects by the EPA, DOE, U.S. Department of Defense (DoD), utilities, and other commercial entities.

Energy*Solutions* received, treated, and disposed of over 1.5 Mgal of waste shipped in ISO tankers from the DOE Rocky Flats closure project. Energy*Solutions* has disposed of more than 85 million ft^3 of waste from DOE sites over the last 25 years.

All wastes received at the Clive facility are entered into and tracked with the Electronic Waste Information System (EWIS). EWIS is an electronic recordkeeping system used to track waste type, volume, activity, and placement location within the disposal embankments. EWIS also contains waste profile information and provides automated compliance checks of the waste shipments against license limits and sampling frequency.

Compliance Monitoring Well Network

A compliance monitoring well network was developed for the CAW embankment. The network includes 27 wells. The monitoring well network is designed to verify regulatory compliance with the state of Utah GWPLs and to provide early warning of potential releases. The spacing of the wells meets the requirement of the Clive facility Ground Water Quality Discharge Permit (UWQB, 2009) for wells to be located no further than 90 ft from the edge of the waste (Part I.F.1.e).

The well spacing analysis was performed and provided reasonable assurance that releases from the CAW embankment can and will be detected. The modeling was performed using ^{129}I and ^{99}Tc as the surrogate contaminants. These radionuclides were selected because of their potential presence in the CAW embankment Class A waste, their conservative transport characteristics (i.e., relatively mobile), and because of their long half-lives relative to the modeled time period of 500 years.

Financial Assurance

Funds for the closure, remediation, and long-term surveillance of the Clive facility are maintained in surety bonds in favor of the Director of the DWMRC. Furthermore, the state of Utah has established a Perpetual Care Fund with a target initial minimum balance of $100 million at the conclusion of the post-closure monitoring period (i.e., year 101 after site closure). The Perpetual Care Fund is funded by an existing cash balance and earnings accrued to this balance. In addition to the estimated costs for decommissioning the Clive facility, the financial surety also covers estimated costs of long-term surveillance of the site. This includes sampling of groundwater monitoring wells, site inspections and repairs, and other miscellaneous costs.

G.2.3 Waste Control Specialists, LLC Waste Disposal Facility (Andrews, Texas)

This section presents a summary of the site conditions, disposal facility design, applicable regulations, waste acceptance criteria, and analyses performed in support of the disposal PA (WCS, 2011) for the WCS disposal facility near Andrews, Texas. This information was collected from multiple sources and presented without further interpretation or reevaluation.

G.2.3.1 Background/General Description

WCS is a treatment, storage and disposal company dealing in radioactive, hazardous, and mixed wastes. Their primary facilities are located on 1,338 acres (540 hectares) of land that is 35 miles (56 km) west of Andrews, Texas and 5 miles (8 km) east of Eunice, New Mexico.

WCS treatment capabilities include dewatering, stabilization and repackaging. Their transportation capabilities include ownership of three Type B shipping casks and two Type A shipping containers. WCS has three separate disposal facilities for radioactive wastes, including (1) a facility for disposal of commercial radioactive wastes from the Texas Low-Level Radioactive Waste Disposal Compact, and radioactive wastes imported from 36 other states into the Texas Compact, (2) a facility for disposal of 11e(2) byproduct material, and (3) the Federal Waste Disposal Facility (FWF). The AEA, as revised in 1978 and in 2005, defines byproduct material in Section 11e.(2) as the tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content (i.e., 11e.(2) byproduct material is uranium or thorium mill tailings).

Figure G-9 is an aerial view of the disposal facilities for radioactive wastes at WCS. The remainder of this subsection focuses exclusively on the FWF, which was designed, licensed, and constructed for federal waste disposal, including all wastes from DOE.

WCS is equipped to receive wastes by truck and by rail. For rail, a receiving building straddles the railhead, and a WCS-owned locomotive brings wastes onsite from nearby Eunice, New Mexico.

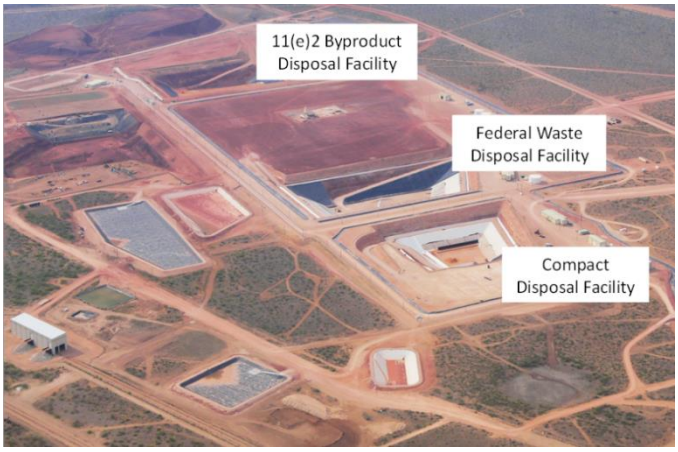


Figure G-9. Waste Control Specialists Waste Disposal Facility

G.2.3.2 Physical Setting

The information in this section was extracted from the following sources:

- Chapter 2 of the WCS Consolidated Interim Storage Facility System Safety Analysis Report (NRC, 2018)
- WCS website (wcstexas.com).

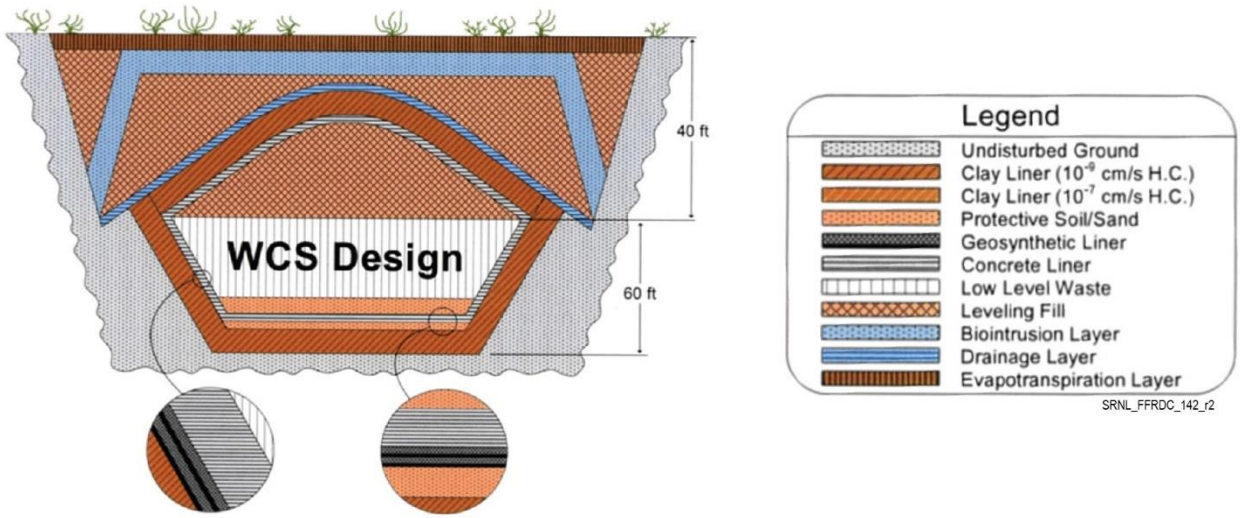
The area surrounding the WCS facilities is sparsely populated and (on average) receives less than 16 in. (400 mm) of rainfall per year. Based on an extensive site investigation program, including over 500 wells and core samples, the geology and hydrology of the WCS site is well understood.

The WCS facilities are located over a geologic feature referred to as the “buried red ridge”. This buried red ridge comprises Triassic-age sediments of the Dockum Group. The Dockum Group consists of a series of fluvial and lacustrine mudstones, siltstones, sandstones, and silty dolomite deposits that are over 1,000 ft thick beneath the WCS site. The buried red ridge (i.e., the Dockum Group) is encountered at depths ranging from about 8 to 80 ft beneath the WCS facilities.

In the subsurface, the Ogallala, Antlers, and Gatuňa geologic formations occur to the north and east of the buried red ridge. These three formations were deposited in different geologic time periods but occupying nearly the same stratigraphic position. The Antlers Formation is the oldest and was deposited in earliest Cretaceous time, whereas the Ogallala Formation is Tertiary in age with deposition occurring between 2 and 6 million years ago. The Antlers formation forms a veneer over the crest of the buried red ridge, with the Ogallala lying to the northeast and Gatuňa lying to the southwest of the ridge.

G.2.3.3 Disposal Facility Design

Wastes are emplaced 25 to 120 ft (~8 to 37 m) below the land surface in the FWF disposal cell that includes a 7-ft (2 m) thick multi-barrier liner. When constructed, the multi-barrier cap over the cell will be a minimum of 25 ft (~8 m) thick and will be completed at-grade. Higher-activity Class B and C LLW and MLLW are disposed of in modular concrete canisters (MCC) inside the disposal cell. The MCCs are 6-in. (150 mm) thick, steel-reinforced concrete containers. The natural barriers (e.g., no drinking water aquifer and thick red clay beds) and the engineered barriers (e.g., 2 m-thick multi-barrier liner and MCCs) work together to give WCS one of the most robust multi-barrier designs of any Agreement State-licensed LLW disposal facility in the United States. Figure G-10 shows the WCS landfill design.



Source: ML17065A225, 2017, "NRC Site Visit, February 2017," presentation to the U.S. Nuclear Regulatory Commission, Waste Control Specialists, LLC, Andrews, Texas.

Figure G-10. Waste Control Specialists Landfill Design

WCS uses two standard types of MCC: (1) cylindrical: 1.8 m (6 ft) and (2) rectangular: 2.9 m long × 2.3 m wide × 2.8 m high (9 ft-6 in. long × 7 ft-8 in. wide × 9 ft-2 in. high) (internal). Typically, Class B and C LLW, inside a U.S. Department of Transportation (DOT) shipping container, is placed in an MCC, any void space is grouted, and the concrete lid is placed on top. A waste that is disposed of in an MCC is categorized by WCS as a *containerized waste*. In contrast, *bulk wastes* may be shipped in reusable DOT shipping containers, the wastes are not disposed of in the DOT shipping container, and the waste is not placed in an MCC. Bulk waste is acceptable for disposal in the FWF, if the waste is Class A and has a dose rate of <100 mrem at 30 cm (~1 ft). Bulk waste is sometimes disposed of in an MCC (e.g., if the dose rate of the bulk waste is >100 mrem at 30 cm [~1 ft]).

Figure G-11 shows the wastes being loaded into rectangular MCCs inside a disposal cell with components of the multi-barrier liner visible in the background. Note the scale of the disposal cell.

Figure G-11. Wastes Being Loaded into Modular Concrete Canisters at the Waste Control Specialists Disposal Cell

Grout waste forms generated by a vendor are assumed to be placed in 8.4 m^3 (11 yd^3) soft-side containers and shipped to Clive using gondola railcars. The details are discussed in Volume II, Appendix H, Section H.7. Grout that is Class A waste can be disposed of in the soft-side containers in the bulk waste area of the disposal cell. Grout that is Class B or C will be disposed of in an MCC. With a capacity of 8.4 m^3 each (11 yd^3), two soft-side containers will fit in a standard rectangular MCC (allowing 2 in. extra on all four sides and 2 in. extra on top). If the grout waste form is generated at WCS via treatment of radioactive LAW liquids received from Hanford, WCS will then decide on the applicable disposal options.

G.2.3.4 Key Regulatory Requirements

Texas is a NRC Agreement State, and the Texas Commission on Environmental Quality (TCEQ) is responsible for licensing and inspecting the WCS radioactive and mixed waste disposal facilities. In August 2004, WCS submitted an application for a radioactive materials license to build and operate their first LLW disposal facility. For licensing the FWF, TCEQ used their state regulations that are equivalent to the 10 CFR 61 licensing requirements. After a detailed multi-year licensing process, in 2009, TCEQ issued a Radioactive Materials License to WCS to dispose of LLW (TCEQ, 2009).

TCEQ approved major construction in 2011, and in 2012 the first radioactive wastes were received for disposal. The FWF is licensed to accept Class A, B and C LLW and Class A, B and C MLLW for disposal. Before disposal, all waste must meet LDR requirements in 40 CFR 268 (or state equivalent LDR requirements).

The FWF is licensed for up to 26,000,000 ft^3 (~736,000 m^3) and 5,600,000 total curies of wastes. The FWF is designed to be built in 11 phases. Only the first of the 11 phases has been completed, as shown in Figure G-9. The Class B and C waste will take about 16% of the maximum allowable containerized volume. The space not taken by the Class B and C waste can be used for Class A waste. Disposing of all waste at WCS will take from 28% to 52% of the available disposal volume and will be 3% to 16% of the total activity limit (Volume II, Appendix H, Section H.6.2).

The term of the current license is through September 2024, with provision for 10-year renewals thereafter. The state of Texas takes ownership of LLW disposed of in the Compact Disposal Facility, and DOE has signed an agreement to take ownership of the FWF after its closure. In post-closure, DOE will be responsible for the waste forms disposed of at the WCS disposal facility.

In addition to the license issued by the TCEQ, WCS maintains other permits and licenses, which are listed on their website (WCS, 2022).

G.2.3.5 Waste Acceptance Criteria

The waste acceptance criteria for the FWF are included as an amendment to the TCEQ license for the FWF, and these criteria are detailed in the WCS *Federal Waste Disposal Facility (FWF) Generator Handbook* (WCS, 2015).

The waste acceptance criteria for the FWF include limits on free liquids (<1% of the volume of containerized waste), maximum void space limits, transportation requirements, and prohibited waste types. Prohibited wastes include high-level radioactive waste, waste capable of generating toxic gases (excluding radioactive gases), and waste readily capable of detonation or of explosive decomposition or reaction at normal pressures and temperatures or of explosive reaction with water.

Some of the general packaging requirements are:

- Each container can only contain one approved profiled (characterized) waste stream
- Packages should weigh 10,000 lb (4,545 kg) or less, unless special arrangements have been made
- All containers transported on public roads to WCS are required to meet the applicable DOT regulations
- Except for bulk wastes and large components, waste packages must fit in an MCC.

The wastes disposed of at WCS must comply with the LDRs detailed in 40 CFR 268.

The radiological waste acceptance criteria for the FWF are based on the NRC's classification system, which divides LLW into classes for disposal – with Class A LLW being the least hazardous and greater-than-Class C (GTCC) LLW being the most hazardous. The NRC describes these classes in 10 CFR 61.55, "Waste Classification." The FWF is licensed for disposal of Class A, Class B, and Class C (as defined in 30 TAC 336.362, "Appendix E. Classification and Characteristics of Low-Level Radioactive Waste") LLW and MLLW and bulk Class A LLW and MLLW in reusable packages with dose rates <100 mrem/hr at 30 cm (~1 in.).

WCS provides two tables for classifying wastes as Class A, B or C for disposal; GTCC wastes are currently prohibited. The two tables from the FWF Generators Handbook (WCS, 2015) are included as Table G-8 for long-lived nuclides and Table G-9 for short-lived nuclides. Volume II, Appendix H, Section H.6 provides details on how the waste class determination was performed for the Hanford LAW.

Table G-8. Table I Class A and C Waste – Long-Lived Isotopes

Radionuclide	Class A Limit		Class B Limit		Class C Limit	
^{14}C	0.8	Ci/m^3	[a]	Ci/m^3	8	Ci/m^3
^{14}C in activated metals	8	Ci/m^3	[a]	Ci/m^3	80	Ci/m^3
^{59}Ni in activated metals	22	Ci/m^3	[a]	Ci/m^3	220	Ci/m^3
^{94}Nb in activated metals	0.02	Ci/m^3	[a]	Ci/m^3	0.2	Ci/m^3
^{99}Tc	0.3	Ci/m^3	[a]	Ci/m^3	3	Ci/m^3
^{129}I	0.008	Ci/m^3	[a]	Ci/m^3	0.08	Ci/m^3
Alpha-emitting transuranic radionuclides with half-lives greater than 5 years	10	nCi/g	[a]	nCi/g	100	nCi/g
^{241}Pu	350	nCi/g	[a]	nCi/g	3,500	nCi/g
^{242}Cm	2,000	nCi/g	[a]	nCi/g	20,000	nCi/g
^{226}Ra[b]	10	nCi/g	[a]	nCi/g	100	nCi/g

Source: Table I of WCS, 2015, *Federal Waste Disposal Facility (FWF) Generator Handbook*, Rev. 4, Waste Control Specialists, LLC, Andrews, Texas.

[a] There are no limits established for these radionuclides in Class B wastes.

[b] This isotope is not listed in the classification tables in 10 CFR 61 but is required by the state of Texas to be included in classification determination.

Table G-9. Table II Class A, B and C Waste – Short-Lived Isotopes

Radionuclide	Class A Limit		Class B Limit		Class C Limit	
Total radionuclides with half-lives less than 5 years	700	Ci/m^3	[a]	Ci/m^3	[a]	Ci/m^3
^{3}H	40	Ci/m^3	[a]	Ci/m^3	[a]	Ci/m^3
^{60}Co	700	Ci/m^3	[a]	Ci/m^3	[a]	Ci/m^3
^{63}Ni	3.5	Ci/m^3	70	Ci/m^3	700	Ci/m^3
^{63}Ni in activated metals	35	Ci/m^3	700	Ci/m^3	7,000	Ci/m^3
^{90}Sr	0.04	Ci/m^3	150	Ci/m^3	7,000	Ci/m^3
^{137}Cs	1	Ci/m^3	44	Ci/m^3	4,600	Ci/m^3

Source: Table II of WCS, 2015, *Federal Waste Disposal Facility (FWF) Generator Handbook*, Rev. 4, Waste Control Specialists, LLC, Andrews, Texas.

[a] There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes. These wastes shall be Class B unless the concentrations of other radionuclides in Table II determine the waste to be Class C independent of these radionuclides.

Table I and Table II (reproduced as Table G-8 and Table G-9) are used to classify wastes as Class A, B, C for disposal. Some points on the use of the tables include:

- Each limit is the full limit. For example, if ^{14}C is the only nuclide in the waste and the concentration is 8 Ci/m^3, the waste would be classified as Class C; any other Table G-8 nuclide, or any additional amount of ^{14}C would require the waste to be classified as GTCC.
- If there are multiple long-lived nuclides (Table G-8 nuclides), the fractional contribution of each nuclide must be calculated and the sum of those fractional contributions must be less than 1 for a given class of waste. The use of the sum of fractions to determine waste classification is explained in 10 CFR 61.55(a)(7).
- If a waste contains long-lived (Table G-8) nuclides AND short-lived (Table G-9) nuclides, the waste form will be classified based on the classification of the long-lived (Table G-8) nuclides, unless a higher classification is derived from the short-lived (Table G-9) nuclides.

G.2.3.6 Hydrogeology

The WCS facility is sited on the 600-ft-thick nearly impermeable red-bed clay formation of the Dockum Group. The upper portion of the Dockum Group is unsaturated. The first from the surface laterally continuous, and continuously saturated, transmissive zone is encountered at the depth of 225 ft. This zone is comprises sandstone/siltstone and is 10 to 35 ft thick. This unit is referred to as the 225-ft zone and has a very low permeability. Measurements of the horizontal hydraulic conductivity of the 225-ft zone range between 10^{-8} cm/s to 10^{-9} cm/s, with one value in the 10^{-7} range. The average was 3.59×10^{-8} cm/s (WCS, 2007, Appendix 2.6.1). Water is estimated to have been present in the 225-ft zone since the Pleistocene and has not led to saturated conditions in the deposits above the 225-ft zone.

Due to low hydraulic conductivity, the 225-ft zone does not yield sufficient volume to support an individual. The TDS of samples from the 225-ft zone ranges from 3,800 to 4,700 mg/L, which means that the water is not potable. The water that is above 1,200 mg/L is generally considered to be unacceptable for human consumption. EPA has established National Secondary Drinking Water Regulations that set the SMCL for TDS at 500 mg/L.

Groundwater in the Dockum Group deposits is generally of poor quality. “Water quality ranges from fresh in the outcrop areas to brine in the confined parts of the aquifer. It also tends to deteriorate with depth, and TDS concentrations can exceed 60,000 mg/L in the deepest parts of the aquifer.” (TWDB, 2003).

There are three distinct formations in the same stratigraphic position immediately above the Cooper Canyon Formation: (1) the Ogallala Formation northeast of the buried ridge, (2) the Gatuna formation southwest of the buried ridge, and (3) the Cretaceous Antlers Formation over the crest of the buried ridge. Elsewhere in the vicinity of the WCS site are Cretaceous shales and limestone (the Comanche Peak/Fort Terrett Formation) overlying the Antlers. These formations are present in this configuration because the buried ridge was a surface drainage divide throughout the late Cenozoic (Hawley, 1993), with Tertiary to Quaternary fluvial material (fluvial sediments of the Ogallala and Gatuna) deposited on either side of the ridge, and the Cretaceous Antlers Formation likely acting as an erosion resistant cap over the crest of the ridge (WCS, 2007). These three formations are combined into a single hydrostratigraphic unit referred to as the OAG (Ogallala, Antlers, and Gatuna) unit. These formations are in lateral hydraulic continuity from a hydrogeologic perspective; however, they are largely unsaturated in the vicinity of the WCS waste facilities.

Table G-10 provides the hydraulic conductivities of the major hydrostratigraphic units (WCS, 2007, Appendix 2.6.1). An estimated vertical velocity beneath WCS is up to 0.02 mm/yr for the current climate conditions and from 0.01 to 0.3 mm/yr for the future climate conditions.

The Ogallala aquifer, which consists of the Ogallala Formation, is the primary freshwater aquifer within the regional study area and serves as the principal source of groundwater in the Southern High Plains (Cronin, 1969; TWDB, 2011). However, the Ogallala Formation is not present beneath the WCS licensed facility (TWDB, 2011).

Table G-10. Hydraulic Conductivities of the Major Hydrostratigraphic Units

Hydrostratigraphic Unit	Hydraulic Conductivity (cm/s)
Cooper Canyon Claystone/ Upper Dockum	4.03×10^{-9}
225-Foot Zone	3.59×10^{-8}
125-Foot (Dry)	5.25×10^{-8}
OAG (Dry)	1.0×10^{-3}
Surface Soil	1.76×10^{-3}
Caprock	1.06×10^{-6}
Clay Cover	4.0×10^{-9}

OAG = Ogallala, Antlers, and Gatuna.

The nearest deposits of the Ogallala Formation occur northeast of the buried ridge near the northeastern corner of the facility, approximately 1 mile northeast of the disposal facilities and represent the southern feather edge of the Ogallala Formation. The Ogallala Formation that is northeast of the facility is not indicative of a productive Ogallala aquifer at that location. The limits of the Ogallala Aquifer have been established as being approximately 10 miles north of the facility.

G.2.3.7 Disposal Performance Evaluation

The disposal PA (WCS, 2011) examines site features such as geology, surface water and groundwater, potential future weather changes, residential and intrusion scenarios, and possible future uses of the land. The WCS PA meets all Texas requirements during the performance period that goes far beyond the federally recommended compliance period of 10,0000 years after site closure.

Source Term

When considering transport in the porous-medium water phase, the radionuclides are assumed to be uniformly distributed and available for leaching by a conservative partition coefficient (K_d) exchange leaching model. This leaching model conservatively assumes that all the radionuclides are available for contact with water and migration. No credit is taken for waste containers, concrete canisters, or improved waste forms such as activated metals or solidified or encapsulated wastes. The entire radionuclide inventory is immediately available for release and transport (WCS, 2007, Appendix 8.0-6).

Although gaseous waste is not disposed of at WCS, to be highly conservative the gaseous source term is estimated by assuming the entire inventories of radionuclides such as ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I are available for immediate release in the gaseous phase. This assumption is highly unrealistic but provides an upper bound dose for compliance purposes. The radon source term is dependent on ingrowth from the ^{226}Ra inventory.

Irradiated metals are assumed to not immediately give up their radionuclide content to the surrounding materials. Rather, as these disposed contaminated metals slowly degrade, they release radionuclides as the metal is lost. This process is modeled as a first order decay process, where a given fraction of the remaining metal is lost to degradation in any given year. This activated metal corrosion rate has been estimated to be 10^{-5} yr^{-1}. The release rate from activated metal is based on measurements of carbon steel and stainless-steel corrosion rates (ANL-DSDMD-00001, *Aqueous Corrosion Rates for Waste Package Materials*). This value has been given some uncertainty by assigning it a normal distribution with a standard deviation of 10^{-6} yr^{-1}.

The chosen fractional release rate is consistent with those used in multiple DOE PAs at Idaho National Laboratory:

- DOE/ID-10978, Pe*rformance Assessment for the Idaho CERCLA Disposal Facility*
- DOE/ID-11421, *Performance Assessment for the Remote-Handled Low Level Waste Disposal Facility*
- DOE/NE-ID-11243, *Performance Assessment for the RWMC Active LLW Disposal Facility*.

Surface Water Pathway

The surface water pathway was determined to be irrelevant for contaminant release. A combination of several factors act to reduce the amount of surface water in the vicinity of the WCS disposal site, which includes all disposal units and a buffer zone. The site is in a semi-arid region where the loss of water by evapotranspiration exceeds precipitation received, there are no perennial streams on or near the site. Surface soils are permeable, and the topography promotes good drainage of the facility area. Additionally, the facility closure will enhance its long-term stability. The ground surface at the disposal site will be contoured to approximate the original stable ground surface. The contours will divert surface water from the disposal units, promote runoff, and help prevent water and wind erosion. A natural vegetative cover will be established that will help stabilize and maintain the soil surface and minimize erosion. The water diversion features and the vegetated cover also serve to minimize water infiltration into the disposal units, which further promotes site stability (WCS, 2011).

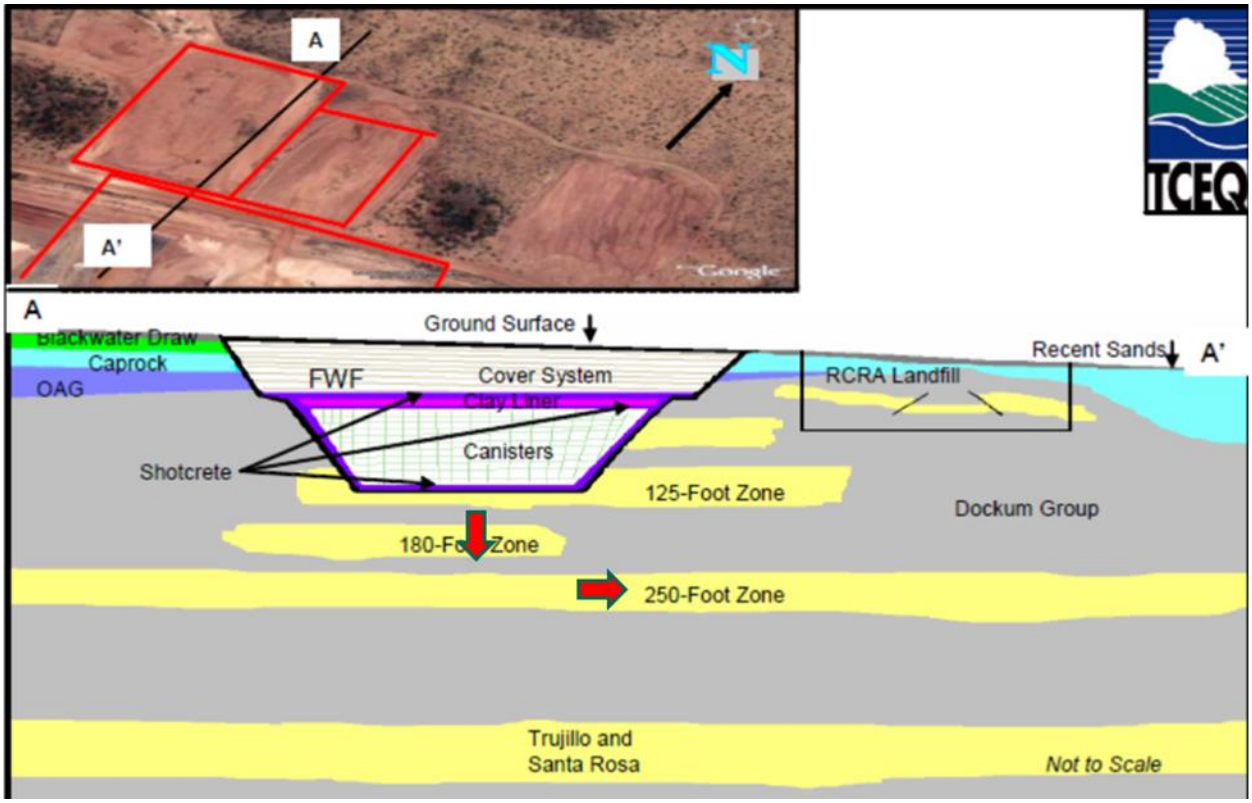
Air Pathway

The air pathway for the WCS Site Model is largely driven by gas emanation through the finished cover where doses from gaseous radionuclides released through the finished earthen cover are calculated (WCS, 2007, Section 8, Appendix 8.0-6). As suggested by NUREG-1573, *A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities*, tritium, ^{14}C, ^{85}Kr, ^{129}I, and radon are considered. The long-lived ^{129}I is considered in the gas emanation pathway as it is does not decay before diffusing through the thick cover. As such, the air pathway is the main risk driver for longer lived, highly mobile radionuclides such as ^{129}I or ^{14}C. Given that ^{99}Tc is a very weak gamma emitter, it will have an insignificant effect on the external gamma dose resulting from the inadvertent intruder scenario (WCS, 2011). HYDRUS analysis of the site has shown that there will be essentially no infiltration though the cover (WCS, 2011). Transport in the water phase is dominated by diffusion where long-lived, mobile radionuclides (e.g., ^{99}Tc) will diffuse upward, affecting pathways that are sensitive to surface uptake factors. Therefore, ^{99}Tc will primarily contribute to produce and soil ingestion pathways.

Groundwater Pathway

Although there are no potable water sources in the area near the WCS facility and very low vertical velocity beneath the WCS site, the groundwater pathway was analyzed in detail and potential impacts were quantified. The conclusion of these analyses was that there is no realistic groundwater pathway at WCS (WCS, 2011).

The hydrogeologic conceptual model for the PA focused on downward movement of infiltration from precipitation through the cover system, the waste, and the lower compacted clay and high-density polyethylene liners, into the undisturbed Cooper Canyon Formation (WCS, 2011). The conceptual hydrogeologic cross-section is shown in Figure G-12.



Source: Reproduced from Figure EA-4 in TCEQ (2008). Note: The 225-foot zone is called 250-foot zone in the source figure and 225-foot zone elsewhere.

Figure G-12. Waste Control Specialists Conceptual Hydrogeologic Cross-Section

The large-scale regional OAG groundwater system was modeled using MODFLOW-SURFACT[1] (WCS, 2011) and the HYDRUS model was used to evaluate infiltration rates. The results of the HYDRUS modeling indicated downward fluxes for current climate conditions range from approximately 0 to 0.02 mm/yr and from 0.01 to 0.3 mm/yr for future-climate conditions (WCS, 2011). These values are much less than the 1 mm/yr flux used in the license application.

[1] MODFLOW-SURFACT is a registered trademark of HydroGeoLogic, Inc., Reston, Virginia.

For the dose calculations, it was assumed that radionuclides leach from the waste, transport through the red clay to the 225-ft zone, and that groundwater is withdrawn from a well at the edge of the disposal facility. Water is used for drinking and livestock watering. The water is assumed to be potable despite the low yield and high dissolved solids. Because a well in the 225-ft zone would not yield sufficient water to meet groundwater requirements for a household or for livestock in a year, the balance is assumed to be provided from an uncontaminated external source.

In the updated PA from 2011 (WCS, 2011), the realistic groundwater pathway dose was determined to be zero. However, the original groundwater pathway based on the 225-foot zone is retained in the PA model as a legacy scenario.

Key Exposure Pathways

The key exposure pathways and the corresponding dose limits and dose standards are provided in Table G-11. Gaseous diffusion and corresponding inhalation dose is the dominant exposure pathway.

Table G-11. Key Exposure Pathways, Dose Limits and Dose Standards

Receptor	Key Exposure Pathways	Dose Limit (mrem/year)	Dose Standard
Post-Institutional Control Period			
Intruder driller	• Diffusion; gas emanation through cover: gas inhalation • Oil well drill cuttings in an open mud pit: external irradiation	500	DOE M 435.1-1[a]
Intruder resident	• Diffusion; gas emanation through cover: gas inhalation (indoor and outdoor) • Ingestion produce grown on contaminated surface soil • Oil well drill cuttings in an open mud pit: external irradiation	500	DOE M 435.1-1[a]
Adjacent resident	• Diffusion; gas emanation through cover: gas inhalation	25	30 TAC 336.724[b]

[a] DOE M 435.1-1, 2011, *Radioactive Waste Management Manual*, Change 2, U.S. Department of Energy, Washington, D.C.

[b] 30 TAC 336.724, "Protection of the General Population from Releases of Radioactivity," *Texas Administrative Code*, as amended.

Figure G-13 shows the scenarios considered in the inadvertent intruder pathway. The dose limit for this pathway is 500 mrem/yr.

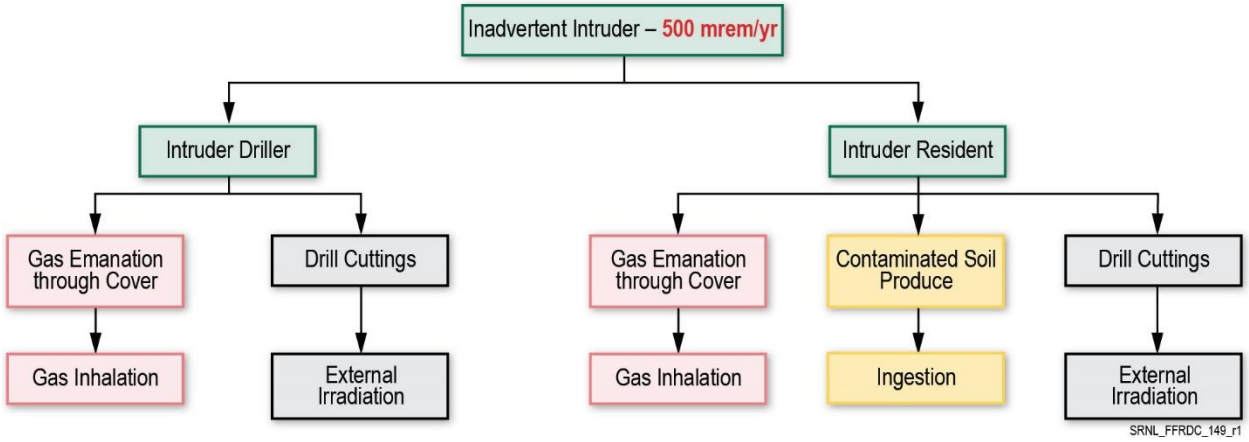


Figure G-13. Scenarios Considered in the Inadvertent Intruder Pathway

Figure G-14 shows the scenarios considered in the general member of the public pathway. The dose limit for this pathway is 25 mrem/yr.

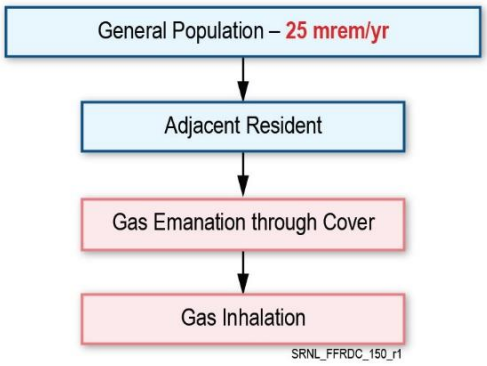


Figure G-14. General Member of the Public Pathway

Period of Compliance

Per 30 TAC 336.709 (1), "A minimum period of 1,000 years after closure or the period where peak dose occurs, whichever is longer, is required as the period of analysis to capture the peak dose from the more mobile long-lived radionuclides and to demonstrate the relationship of site suitability to the performance objective in this section to the performance objective in Section 336.724 of this title."

The current disposed FWF inventory at WCS has a peak dose of approximately 0.009 mrem/year at 564,000 years from closure of the facility and is driven by ^{226}Ra.

When waste intrusion is considered in accordance with NUREG/CR-4370, waste can be brought to the surface following the loss of institutional controls (post-IC). For radionuclides with low transport mobility, this greatly reduces the time for corresponding peak doses to occur and in the case of strontium-90 (^{90}Sr) and cesium-137 (^{137}Cs), allows for such radionuclides to reach the surface of the WCS Site Model and contribute to dose pathways with a negligible peak in the range of 5.0×10^{-7} to 4.0×10^{-9} mrem per year before complete decay removal occurs.

Although the doses are small fractions of a mrem per year, (comparable to ^{90}Sr and ^{137}Cs) short-lived, high mobility radionuclides like ^{3}H will have a peak dose in the first 100 years following loss of institutional controls, regardless of waste intrusion. Like short-lived, highly mobile radionuclides long-lived, high mobility radionuclides like ^{129}I and ^{14}C will have peak doses between years 10,000 and 100,000 when there is no waste intrusion. When waste intrusion is considered, this time to peak is reduced to less than 10,000 years signifying a loss mechanism to the atmosphere via gaseous diffusion. Waste intrusion has no real impact on peak dose timing for other long-lived, high mobility radionuclides whose transport is not driven by gaseous diffusion (i.e., ^{99}Tc). Long-lived, low mobility radionuclides, such as Se-79, tend to have a peak dose occur beyond the 1,000,000-year point if there is no waste intrusion.

The special case of Rn-222 requires sufficient time for in-growth. Considering future climate conditions yields a dose of 1×10^{-8} mrem per year which is well below the point of compliance and occurs around 1,000,000 years post-closure. Table G-12 provides timing of the peak doses for short-lived and long-lived radionuclides with different mobilities.

Table G-12. Timing of Peak Doses for Short-Lived and Long-Lived Radionuclides with Different Mobilities

Decay Classification	Transport Classification	Radionuclide Example	Time of Peak Dose with No Waste Intrusion (years post-IC)	Time of Peak Dose with Waste Intrusion (years post-IC)
Short-lived	Low mobility	^{90}Sr, ^{137}Cs	N/A	0
Short-lived	High mobility	^{3}H	0-100	0-100
Long-lived	Low mobility	^{79}Se	1,000,000+	10,000-100,000
Long-lived*	High mobility	^{129}I, ^{14}C	10,000-100,000	1,000-10,000
Long-lived	High mobility	^{99}Tc	100,000-1,000,000	100,000-1,000,000
In-growth	High mobility	^{222}Rn	1,000,000+	1,000,000+

IC = institutional control.

G.2.3.8 Confidence in Successful Disposal

Texas is an Agreement State and has a bifurcated regulatory structure designating the TCEQ to oversee the disposal of radioactive waste and the Texas Department of State Health Services to oversee the generation of radiation and radioactive material.

Public Participation

The requirement for public participation in Texas is driven by the Texas Health and Safety Code (TCAS) 401.232(b) which states "The commission shall conduct at least one public meeting in the county or counties where a compact waste disposal facility or federal facility waste disposal facility is to be located to receive public comments on the administratively complete applications. The commission shall set the time and place of the meetings as soon as practicable after the close of the period for administrative review of the applications."

As the WCS FWF is also a permitted hazardous waste facility, there are also requirements for public meetings and notifications in TCAS Section 361.082 and Section 361.091. For Radioactive Materials License R04100, WCS conducted multiple public meetings in Andrews and Austin Texas, in addition to the multiple opportunities for public comment provided by cognizant state agencies, including after receipt of the initial license application Notification of Declaration of Administrative Completeness and again after the Notice of Completion of Technical Review. After the approval of Radioactive Materials License R04100, similar public postings and opportunities are available for public interaction through all minor and major amendments of Radioactive Materials License R04100, which is now on Amendment 38 (TCEQ, 2009). Each public posting is made in the Texas Register, the local Andrews, Texas and Hobbs, New Mexico papers, and postings at the Andrews, Texas public library. WCS enjoys a robust and open working relationship with TCEQ and encourages the two TCEQ Resident Inspectors to monitor and review site activities, including processing and treatment.

Multiple opportunities for public participation were provided in the form of public meetings in Andrews and Austin (sponsored by both WCS and TCEQ) and in agency written public comment periods during both the initial license approval process and subsequent amendments.

WCS supports a Compatibility C standard, which would allow TCEQ to continue its current level of licensing and site scrutiny to ensure that WCS is not just environmentally protective but also continues to share the confidence of the local community.

Waste Ownership

Upon receipt, Texas Compact LLW ownership is transferred to the state of Texas and federal LLW is transferred to DOE after post-closure of the FWF.

Retrievability

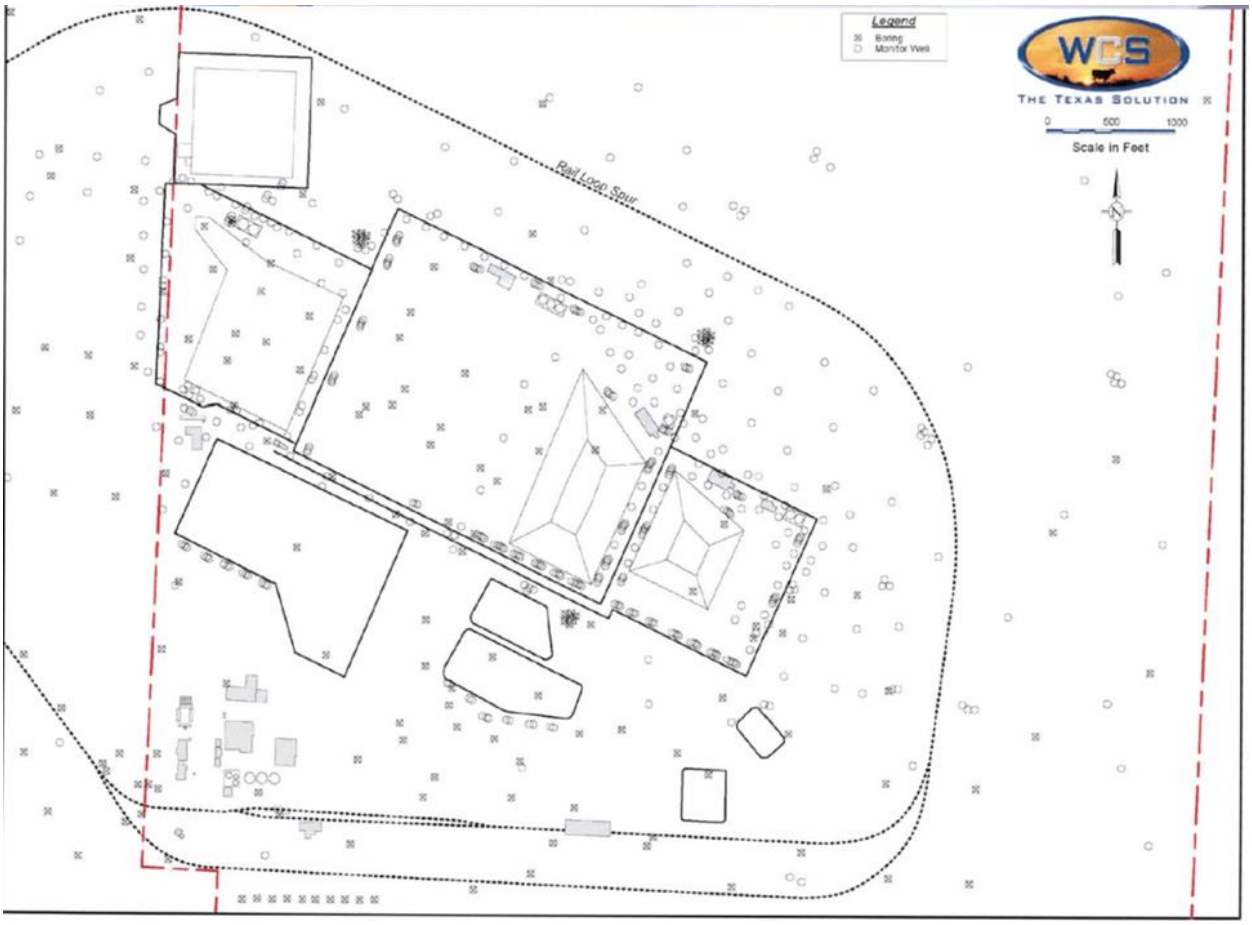
The Class B and C waste will be disposed of in MCCs. MCC placement allows for waste retrievability via global positioning system technology.

Regional Groundwater Model

The OAG model was calibrated to observations of wet and dry conditions in 231 wet and dry wells on the WCS site and vicinity. The normalized root mean square error was 6%, indicating the calibration was of good quality (Anderson and Woessner, 1992). The calibrated model was used to simulate two transient events and produced results consistent with the regional flow system (WCS, 2011). Although the Ogallala aquifer OAG is not part of the PA model as the Ogallala formation is not below the facility, the OAG unit was used in the HYDRUS modeling to determine the appropriate and very low infiltration rates used in the PA model.

Monitoring Well Network

Over 640 wells determined geologic characteristics and confirmed that the WCS facility is not over an aquifer. Over 400 monitoring wells are measured quarterly, many of which are dry. Approximately 150 monitoring wells are laboratory sampled semi-annually if there is enough water. Figure G-15 shows the WCS monitoring well network.



Source: ML17065A225, 2017, "NRC Site Visit, February 2017," presentation to the U.S. Nuclear Regulatory Commission, Waste Control Specialists, LLC, Andrews, Texas.

Figure G-15. Monitoring Well Network at Waste Control Specialists

Erosion Monitoring

As part of the WCS license application in 2007, erosion monitoring stations were installed on the site and erosion monitoring was incorporated into the site's monitoring program (WCS, 2007, Appendix 4.4-1). In 2018, WCS completed a 12-year study of erosion at the WCS site (TCEQ, 2009, Amendment 31 [2018], Appendix 8.0). Based on the measurement data presented in the study, the conclusion was that that the site was experiencing a net accumulation of sediment instead of erosion.

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Appendix H. Transportation and Off-Site Disposal

H.1 INTRODUCTION

This appendix describes the programs that will be needed to transport liquids, grout, and fluidized bed steam reforming (FBSR) waste forms from the Hanford Site to the Waste Control Specialists, LLC (WCS) Waste Disposal Facility (Texas) and Energy*Solutions* Clive Disposal Facility (Utah). The following topics are addressed:

- General evaluation assumptions and approach
- Key regulatory considerations for packaging and transportation
- Low-specific activity (LSA) determination
- Waste acceptance criteria
- Packaging and packaging requirements
- Transportation routes and schedules
- Transportation and waste form disposal costs
- Nonmonetary considerations related to transport
- Technology Readiness Level (TRL)
- Technical risks
- Programmatic risks.

H.2 GENERAL EVALUATION ASSUMPTIONS AND APPROACH

For this analysis, current conditions are assumed to prevail. This means that the analysis is based on the current railroads, the current regulatory requirements for shipping, and the current shipping and packaging technologies.

Basing the analyses on current conditions prevents undue speculation about future conditions, while allowing an even-handed comparison of disposal of grout and FBSR waste forms at the off-site disposal facilities. Based on the existing physical capacities of the Clive and WCS facilities, all Class A grout or FBSR LAW waste forms can be disposed of either at Clive or WCS. Based on the existing WCS facility physical capacity, all Class B and C grout or FBSR LAW waste forms can be disposed of at the WCS disposal facility.

All calculations were performed using two feed vectors – SP9 1B and Early Start. The feed vectors are provided using a monthly average concentration of 46 radionuclides for each month of waste generation. Feed vector SP9 1B represents the conditions in alternatives FBSR 1B and Grout 4B. The Early Start feed vector represents the conditions in alternative Grout 6. In Grout 6, off-site disposal is assumed until 2040. The analysis considered this alternative and the alternative in which all waste is disposed of offsite, which provides the information in case the on-site disposal cannot be realized. The transportation and disposal of FBSR is briefly discussed. The discussion is limited because FBSR is not one of the four alternatives selected to be evaluated in detail. Note that the liquid-to-solid volumetric ratio was conservatively assumed to be 1.2 in calculations related to FBSR. The larger ratio results in a larger FBSR waste volume. The FBSR volumetric ratio assumed in all other analyses discussed in this report was 1.0.

H.3 KEY REGULATORY CONSIDERATIONS

Per DOE O 460.1D, *Hazardous Materials Packaging and Transportation Safety*, DOE has broad authority under the *Atomic Energy Act of 1954* (AEA), as amended, to regulate activities involving radioactive materials that are undertaken by DOE or on its behalf, including the transportation of radioactive materials. In most cases that do not involve national security or other critical interests, DOE uses commercial carriers that undertake its shipments subject to regulation by the U.S. Department of Transportation (DOT) and U.S. Nuclear Regulatory Commission (NRC), as appropriate.

However, DOE exercises its AEA authority to regulate certain DOE shipments, including shipments by government employees and on-site transfers. In all cases, DOE's packaging and transportation activities must be conducted in a manner that achieves an equivalent level of safety to that required by DOT and NRC for comparable commercial shipments.

The NRC regulates the packaging for the transport of radioactive materials. The DOT coordinates with the NRC to set rules for the packaging. The DOT also works with the NRC and affected states to regulate their transport.

H.3.1 10 CFR 71 Packaging and Transportation of Radioactive Material

Title 10, *Code of Federal Regulations*, Part 71 (10 CFR 71), "Packaging and Transportation of Radioactive Material," defines the packaging and transportation performance criteria to ensure the safe transport of radioactive materials under normal and hypothetical accident conditions. This NRC regulation uses a graded approach in setting packaging criteria to protect public health and the environment, where:

- LSA[1] materials may be shipped in industrial packages (IP) that are exempt from NRC package certification (but not exempt from DOT requirements)
- Materials that exceed the LSA limits, but are below the "A_2" content limit,[2] must be shipped in Type A packaging
- Higher-activity content materials that exceed the LSA limits and that exceed the A_2 content limit must be shipped in Type B packaging, which meets the most stringent criteria (except for the air-transport criteria).

The methodology and tables for determining if the amount of activity in a container exceeds the A_2 limit are presented in Appendix A of 10 CFR 71.

All packages for shipping radioactive material (IP, Type A, or Type B) must be designed and prepared so that under conditions normally incident to transportation, the radiation level does not exceed 2 mSv/hour (200 mrem/hour) at any point on the external surface of the package, and the transport index[3] does not exceed 10 (10 CFR 71.47, "External Radiation Standards for All Packages").

The supplemental LAW waste forms are not anticipated to be transported in a Type A container or Type B shipping cask. The waste forms meet the LSA criteria for liquids and solids (Section H.5) and can be shipped in IPs, as addressed below.

Shipping in Industrial Packages

LSA radioactive materials may be shipped as NRC-defined LSA material in IPs that are exempt from NRC certification if the specific activity (the activity per unit mass) of the waste forms is low enough and other requirements are met. As discussed later, the LSA criteria are linked to the A_2 quantity. The three types of LSA materials and requirements that IPs must meet are discussed in detail in Section H.5.

[1] Low-specific activity material means radioactive material with limited specific activity that is nonfissile or is excepted under 10 CFR 71.15, "Exemption from Classification as Fissile Material," and satisfies the descriptions and limits for LSA-I, LSA-II, and LSA-III materials set forth in 10 CFR 71.4, "Definitions." Shielding materials surrounding the LSA material may not be considered in determining the estimated average specific activity of the package contents (10 CFR 71.4).

[2] The A_2 value is the maximum amount of radioactive material (measured in becquerels or curies), other than special form, LSA, and Surface Contaminated Object materials, permitted in a Type A package. This value is either listed in 10 CFR 71, Appendix A, Table A-1, or may be derived in accordance with the procedures prescribed in 10 CFR 71, Appendix A (10 CFR 71.4).

[3] The transport index is the number determined by multiplying the maximum radiation level in mSv/hour at 1 m (3.3 ft) from the external surface of the package by 100 (equivalent to the maximum radiation level in mrem/hour at 1 m [3.3 ft]).

H.3.2 49 CFR 171-173 Hazardous Materials Regulations

49 CFR 171–173 address many facets of the transport of radioactive materials, which are a subset of DOT's broader definition of hazardous materials. Each licensee who transports licensed material on public highways, or who delivers licensed material to a carrier for transport, must comply with the applicable requirements of the DOT regulations in 49 CFR, "Transportation." Some of the activities regulated by 49 CFR 171–173 include:

- Packaging: 49 CFR 173, Subparts A, B, and I
- Marking and labeling: 49 CFR 172, Subpart D; and Sections 172.400 through 172.407 and Sections 172.436 through 172.441 of Subpart E
- Placarding: 49 CFR 172, Subpart F, especially Sections 172.500 through 172.519 and 172.556; and appendices B and C
- Accident reporting: 49 CFR 171, Sections 171.15 and 171.16
- Shipping papers and emergency information: 49 CFR 172, Subparts C and G
- Hazardous material employee training: 49 CFR 172, Subpart H
- Security plans: 49 CFR 172, Subpart I
- Hazardous material shipper/carrier registration: 49 CFR 107, Subpart G
- DOT regulations specific to transport by rail: 49 CFR 174, Subparts A through D and K.
- DOT regulations specific to transport by truck: 49 CFR 177 and 49 CFR 390-397.

The DOT regulations also define "contamination," which means the presence of a radioactive substance on a surface in quantities in excess of 0.4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters or 0.04 Bq/cm^2 for all other alpha emitters. There are two categories of contamination:

1. Fixed contamination means contamination that cannot be removed from a surface during normal conditions of transport.
2. Non-fixed contamination means contamination that can be removed from a surface during normal conditions of transport (49 CFR 173.443, "Contamination Control").

To ensure the appropriate scoping and costing, this study will rely on analogue costs from other programs, where the U.S. Department of Energy (DOE) has shipped radioactive wastes for disposal. In this way, the scope and cost of meeting the above requirements will be captured, without summarizing the large number of safety requirements found in 49 CFR 171–174 for shipping radioactive materials.

H.3.3 U.S. Department of Energy Regulations and Orders

The DOE Office of Packaging and Transportation provides packaging and transportation services to the entire DOE complex. The AEA, as amended, gives DOE broad authorities to regulate all aspects of activities involving radioactive material that are undertaken by DOE or on its behalf, including transportation.

Authorities for the Office of Packaging and Transportation flow from 41 CFR 109-40, "Transportation and Traffic Management," and 49 CFR 173, "Shippers – General Requirements for Shipments and Packagings," which establishes DOE's transportation management and packaging certification authorities, and DOE O 460.1D; DOE O 460.2B, *Departmental Materials Transportation Management*; and DOE M 460.2-1A, *Radioactive Material Transportation Practices Manual*.

DOE O 460.1 establishes safety requirements for the proper packaging and transportation of off-site shipments and on-site transfers of hazardous materials, including radioactive materials. DOE O 460.2B establishes standard transportation practices for DOE elements to use in planning and executing off-site shipments of radioactive material, including radioactive waste.

DOE M 460.2-1 was developed through a collaborative effort under the Senior Executive Transportation Forum (established by the Secretary of Energy in January 1998) to coordinate efforts of Departmental elements involved in the safe transportation of radioactive material and waste. Subsequent updates also reflect the continuing collaboration of DOE and outside organizations, such as the Tribal Caucus and State Regional Groups, on transportation of radioactive material and waste.

The Manual comprises transportation practices that establish a standardized process and framework and include interacting with State, Tribal, and local authorities, other Federal agencies, and transportation contractors and carriers regarding DOE radioactive material shipments.

H.3.4 National Environmental Policy Act

Actual implementation of a large-scale, off-site disposal program, with the associated transportation program, such as outlined in this appendix, may require additional National Environmental Policy Act (NEPA) review. This study is not an environmental impact statement (EIS) and was not scoped to provide a detailed analysis of potential transportation impacts often included in an EIS; however, this section identifies the information needed for an EIS, such as:

- Dose rate on the outside of the shipping package(s)
- Radiological content of the material(s) being shipped
- Form of the waste (solid, powder, liquid)
- Packaging
- Quantities of material(s) being shipped
- Transportation mode
- Routing and population densities along the route
- Most recent emission data
- Most recent accident data for 2013 to 2022.

In addition, Section H.12 compares the risks from disposal of Hanford supplemental LAW to the risks calculated in the EIS for a similar campaign.

H.3.5 U.S. Department of Energy Experience Shipping Hazardous Materials, Including Low-Level Waste

DOE has extensive experience in safely transporting hazardous materials, including liquid low-level radioactive waste (DOE-EM, 2020). About 3 million radioactive materials packages are shipped in the U.S. annually by highway, rail, air, and water. Since 2004, the DOE Office of Environmental Management (EM) has completed over 184,000 shipments of radioactive material and radioactive waste.

DOE has ordering agreements with different commercial companies that are permitted and licensed to treat liquid radioactive waste (DOE-EM, 2022). Examples of liquid radioactive waste shipments from the 2020 fact sheet (DOE-EM, 2020) are provided in Table H-1.

Table H-1. U.S. Department of Energy Liquid Radioactive Waste Shipments

Time period	Liquid	Volume (gal)	DOE facility	Origin	Destination	Transport mode	Purpose
2017	LLW	1,000	West Valley	NY	WCS, TX	Truck	Treatment and disposal
2012	Radiologically contaminated aqueous hydrogen fluoride	4,700	Portsmouth Gaseous Diffusion Plant	OH	WCS, TX	Truck	Treatment and disposal
2010-2020	LLW	150,000	Separations Process Research Unit	NY	Richland, WA	Truck	Treatment and disposal
Up to 2005	LLW	1,500,000	Rocky Flats	CO	Clive, UT		Treatment

CO = Colorado.
DOE = U.S. Department of Energy.
LLW = low-level waste.
NY = New York.
OH = Ohio.
TX = Texas.
UT = Utah.
WA = Washington.
WCS = Waste Control Specialists, LLC.

The DOE transportation program engages state, tribal, and local jurisdictions. One of the venues of such engagement is the National Transportation Stakeholders Forum where all aspects of DOE's shipments of radioactive materials and waste are discussed. The DOE Transportation and Emergency Preparedness Program conducts courses in emergency preparedness with state, tribal, and local emergency responders. This program provides the necessary training and tools to respond to transportation accidents involving DOE-owned radioactive material shipments.

H.3.6 Radioactive Material Transportation Safety

In 2006, the National Research Council's Nuclear and Radiation Studies Board (NRSB) appointed by the National Academies released a report entitled "Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States" (NRSB, 2006). The report is a result of an extensive study of the risks and potential technical and societal challenges associated with the transport of spent nuclear fuel (SNF) and radioactive high-level waste (HLW) in the U.S. During this study, NRSB collaborated with multiple organizations and individuals involved with the transport of SNF and HLW.

The Committee "could identify no fundamental technical barriers to the safe transport of spent fuel and high-level radioactive waste in the United States." Safety refers to measures taken to protect SNF and HLW during transport operations from failure, damage, human error, and other inadvertent acts. The Committee concluded that "current international standards and U.S. regulations are adequate to ensure package containment effectiveness over a wide range of transport conditions" and "radiological health and safety risks associated with the transportation of spent fuel and high-level waste are well understood and are generally low." The potential challenges are related to social and institutional aspects of transporting SNF and HLW.

Another important study in this area was documented in ORNL/SR-2016/261, *Historical Review of the Safe Transport of Spent Nuclear Fuel*. This report provided an analysis of the publicly available information on SNF transportation worldwide. Based on the available information, 25,400 shipments of SNF have been made worldwide. The actual number of shipments was estimated to be 44,400 or more. The shipments within and into the U.S. account for 10% to 17% of world-wide shipments. At least 130 cask shipments of vitrified HLW in more than 2,350 canisters have been reprocessed at the plant in La Hague, France, and shipped back to the countries where the SNF originated.

The report clearly demonstrated that "transportation of SNF has been accomplished routinely and safely in many countries around the world, including the U.S., for decades." Based review of the available data, the study concluded that all shipments "were undertaken without any injury or loss of life caused by the radioactive nature of the material transported." There have been only a few transportation accidents worldwide in the history of transporting SNF. None of these accidents had traceable radiological consequences.

The report described an accident that occurred in the U.S. in 1972 during shipment of a cask with SNF; the most severe accident that has occurred during a shipment of SNF. A truck overturned and the cask got separated from the trailer. However, the cask was only superficially damaged and radioactive materials were not released.

Over the years, the NRC conducted a number of assessments of transportation risks, and their conclusion was that the radiological risks are very low. As an example, in the most recent 2014 NRC risk assessment report (NUREG-2125, *Spent Fuel Transportation Risk Assessment*), during the normal conditions of transport of SNF and HLW, the collective dose to general public was shown to be four orders of magnitude smaller than the naturally occurring background dose received by the same population in the same period of time.

The transport of low level radioactive waste is significantly less challenging with regard to the potential technical and societal challenges, and associated radiological health and safety risks are significantly lower compared to the SNF and HLW. Consequently, the conclusions regarding safe transport of SNF and HLW apply to the transport of other radioactive waste.

H.4 ON-SITE IMPACTS OF OUT-OF-STATE SHIPMENT

A rail spur to the Hanford Site is assumed to be maintained to allow rail transport of solid waste forms, grout or FBSR, or liquid waste to the off-site disposal facilities. The liquid waste form would be converted to grout at the off-site disposal facilities. Alternatively, liquid waste could be transported to a vendor for grouting and then to the off-site disposal facilities. The transport will most likely be by truck. In addition, temporary on-site storage for staging waste might be required. The size of this facility is assumed to be limited, with the facility designed to mitigate any postulated accident event during package handling.

H.5 LOW-SPECIFIC ACTIVITY DETERMINATION

The NRC uses a graded approach in setting packaging and shipping requirements for the transport of radioactive materials. The least hazardous category of materials comprises those materials that qualify as LSA. LSA material is radioactive material with limited specific activity that is nonfissile or is excepted under 10 CFR 71.15, "Exemption from Classification as Fissile Material," and that satisfies the descriptions and limits for LSA set forth in 10 CFR 71.4, "Definitions." The NRC defines three categories of LSA materials: LSA-I, LSA-II and LSA-III. Working in tandem with the NRC, the DOT defines the packaging requirements for transporting these materials. The LSA materials can be transported in IPs. The IPs are exempt from NRC certification and are significantly less expensive compared to Type A and B packages that are used for the materials that do not meet the LSA determination. IP packages are certified by vendors who also provide records demonstrating the packages meet all applicable requirements.

An overview of the three categories of LSA and their classification requirements is provided below.

LSA-I includes materials such as uranium and thorium ores, solid unirradiated natural uranium, or depleted uranium or natural thorium – radioactive material for which the A_2 value is unlimited; or other radioactive material in which the activity is distributed throughout and the estimated average specific activity does not exceed 30 times the value for exempt material activity concentration determined in accordance with Appendix A of 10 CFR 71.

LSA-II includes material in which the activity is distributed throughout and the average specific activity is less than 10^{-4} A_2/gram for solids and gases, and 10^{-5} A_2/gram for liquids or water with tritium concentrations up to 0.8 TBq/L (20.0 Ci/L).

LSA-III includes solids (e.g., consolidated wastes, activated materials), excluding powders, which satisfy the requirements of 10 CFR 71.77, "Qualification of LSA-III Material," in which:

(i) The radioactive material is distributed throughout a solid or a collection of solid objects, or is essentially uniformly distributed in a solid compact binding agent (e.g., concrete, bitumen, ceramic).

(ii) The radioactive material is relatively insoluble or is intrinsically contained in a relatively insoluble material so that even under loss of packaging, the loss of radioactive material per package by leaching when placed in normal pH water for 7 days, would not exceed 0.1 A_2 (see 10 CFR 71.77 for additional details).

(iii) The estimated average specific activity of the solid is less than 2×10^{-3} A_2/gram (10 CFR 71.4).

Other criteria that the three categories of LSA materials must meet are discussed in Sections H.5.2, H.5.3, and H.5.4, and include:

- External radiation at any point on the external surface of the shipping package must not exceed 2 mSv/hour (200 mrem/hour) (10 CFR 71.47(a)).
- The material must have an external radiation dose less than or equal to 10 mSv/hour (1 rem/hour) at a distance of 3 m (10 ft) from the unshielded material (10 CFR 71.14(b)(3)(i)) and 49 CFR 173.427, "Transport Requirements for Low Specific Activity (LSA) Class 7 (Radioactive) Material and Surface Contaminated Objects (SCO)").

H.5.1 Supplemental Low-Activity Waste Specific Activity

The A_2 of a material is needed to determine whether a material meets the concentration limits for shipping as an LSA material. The formula for calculating the A_2 for a mixture of radionuclides is presented in Figure H-1.

The radioactive liquids and FBSR waste form can be transported in IPs if the waste meets the applicable LSA-II requirements for liquids or solids. Grout can be transported in IPs if either the LSA-II requirements or less stringent LSA-III requirements are met.

$$A_2 \text{ for mixture} = \frac{1}{\sum_i \frac{f(i)}{A_2(i)}}$$

where f(i) is the fraction of activity for radionuclide I in the mixture, and $A_2(i)$ is the appropriate A_2 value for radionuclide I.

Source: Appendix A of 10 CFR 71, "Packaging and Transportation of Radioactive Material," *Code of Federal Regulations*, as amended.

Figure H-1. Formula for Calculating the A_2 for a Mixture of Radionuclides

The following calculations were set up to determine whether the LSA-II requirements regarding the average specific activity (less than 10^{-4} A_2/gram for solids and 10^{-5} A_2/gram for liquids) are met for the liquids, grout, and FBSR waste forms. For each month in the feed vector, the total activities (Ci/m^3) of the liquids, grout, and FBSR waste forms were calculated. The assumed volume dilution was 1/1.8 = 0.556 for grout and 1/1.2 = 0.833 for FBSR. The specific activities (Ci/g) of the liquids, grout, and FBSR waste forms were calculated from the corresponding total activities and densities. The liquid density was taken from the corresponding feed vector (Volume II, Appendix B). The grout density was assumed to be 1,770 kg/m^3. The FBSR density was assumed to be 800 kg/m^3.

For each of 46 radionuclides in the feed vector, the radionuclide fraction of the total activity was calculated and divided by the radionuclide A_2 value. The A_2 of the mixture was calculated using the equation in Figure H-1 for each month. The LSA-II criterion for liquids is 10^{-5} × Liquid Mixture A_2. The LSA-II criterion for grout is 10^{-4} × Grout Mixture A_2. The LSA-II criterion for FBSR is 10^{-4} × FBSR mixture A_2.

The calculations were done for two feed vectors –Scenario 1B from the System Plan (ORP-11242, *River Protection Project System Plan*), referred to in this appendix as SP9 1B, and Early Start. The SP9 1B feed vector is used in the FBSR 1B and Grout 4B alternatives considered in this analysis. The total liquid volume in this feed vector is 56.2 Mgal. The waste generation period is from January 2034 to February 2076.

The Early Start feed vector is used in alternative Grout 6. The total liquid volume in this feed vector is 95.2 Mgal. The waste generation period is from March 2028 to November 2064. However, alternative Grout 6 assumes that off-site disposal takes place until 2040. The period until 2064 is also considered to cover the unlikely situation in which on-site disposal becomes unavailable for some reason.

The results of the calculations are plotted in Figure H-2 and Figure H-3 for the SP9 1B feed vector and in Figure H-4 and Figure H-5 for the Early Start feed vector. The concentrations of ^{90}Sr in these feed vectors were adjusted assuming that 99% is removed via TSCR. Although it is known that some marginally soluble transuranic radionuclides (plutonium and neptunium) are also partially removed by crystalline silicotitanate (CST), adjusting feed vectors to take credit for potential removal of the 30% of transuranic radionuclides would have an insignificant impact on the mixture A_2 values. Consequently, no credit is taken for transuranic radionuclides removal in meeting the LSA-II limits for either liquids or solids.

Figure H-2 and Figure H-4 compare the liquids specific activities to the LSA-II limit for liquids. Figure H-3 and Figure H-5 compare the grout and FBSR specific activities to the LSA-II limit for solids. The LSA-III limit for solids is also shown for comparison. The major contributors to the radionuclide mixture A_2 are ^{241}Am and ^{239}Pu. Both liquids and solids (grout and FBSR) meet the corresponding LSA-II specific activity limits during the entire period of operations. The liquids are at least one order of magnitude below the LSA-II limit for liquids, with a few exceptions. Grout and FBSR are at least two orders of magnitude below the LSA-II limit for solids, with a few exceptions. Grout is at least three orders of magnitude below the LSA-III limit for solids, with a few exceptions.

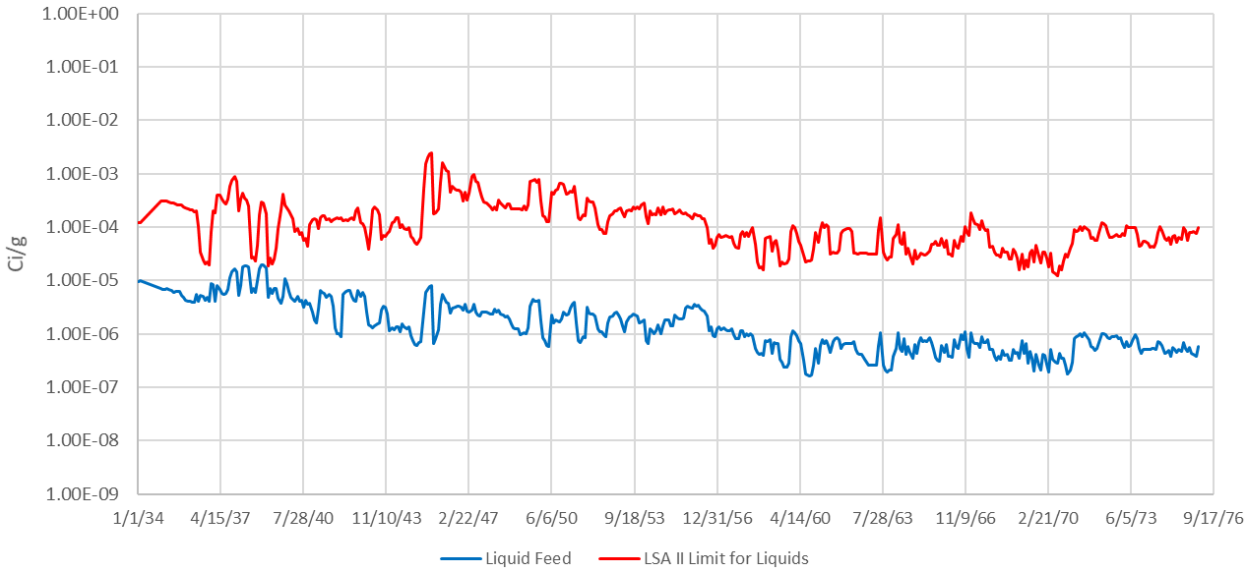


Figure H-2. Feed Vector SP9 1B Liquids Specific Activity Compared to the LSA-II Limit for Liquids

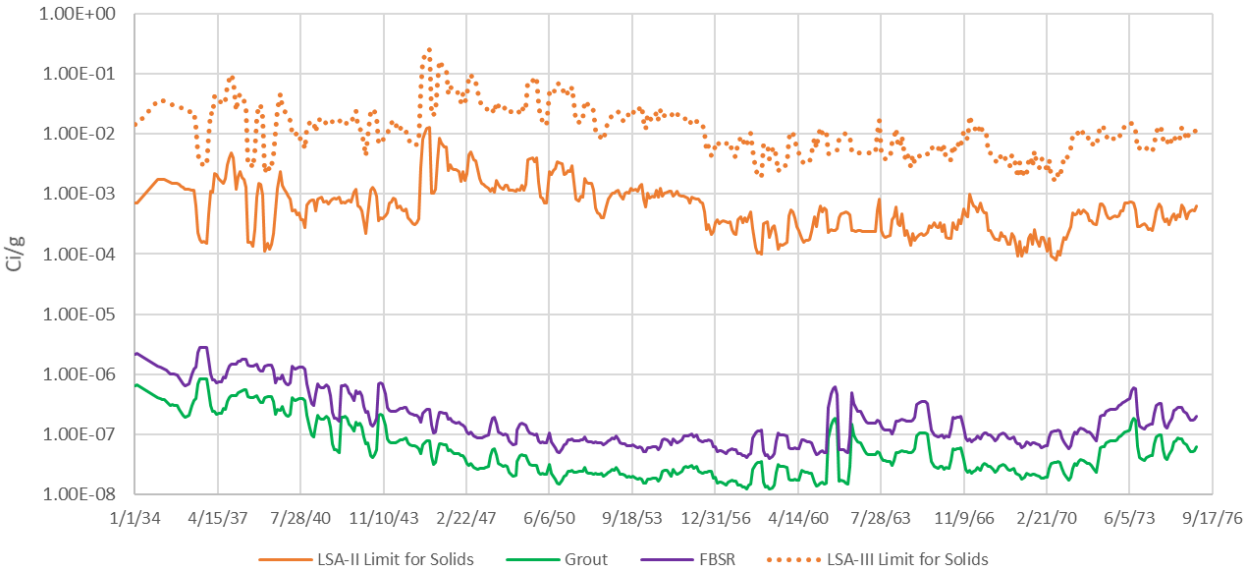


Figure H-3. Feed Vector SP9 1B Grout and Fluidized Bed Steam Reforming Specific Activities Compared to the LSA-II Limit for Solids

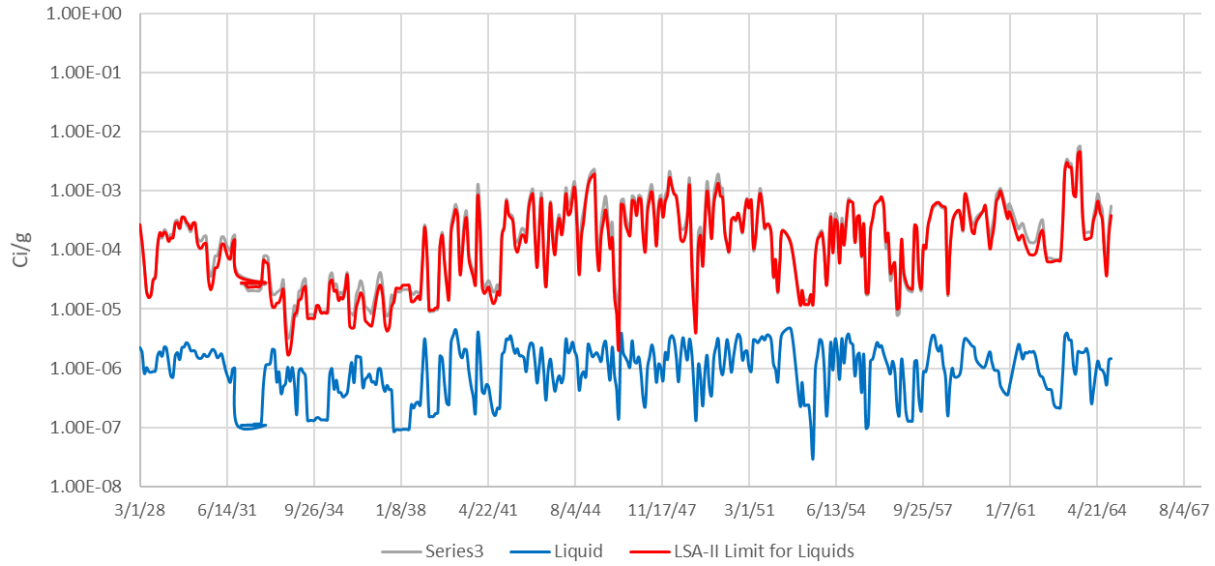


Figure H-4. Early Start Feed Vector Liquids Specific Activity Compared to the LSA-II Limit for Liquids

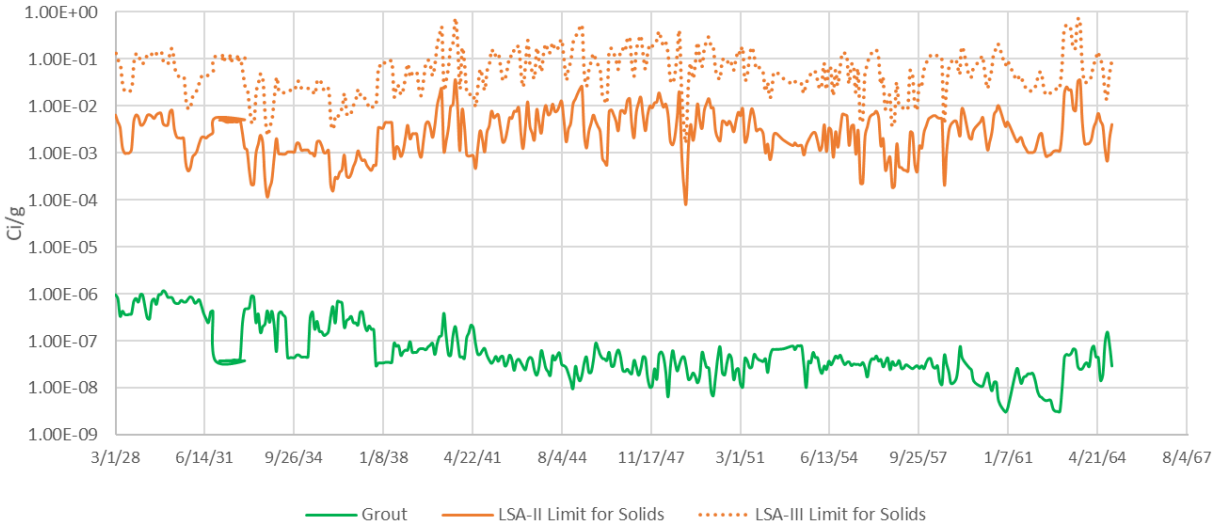


Figure H-5. Early Start Feed Vector Grout Specific Activity Compared to the LSA-II Limit for Solids

H.5.2 Non Fissile Material Exemption

The LSA materials must be nonfissile or must be exempt under 10 CFR 71.15.

Fissile material meeting the requirements of at least one of the paragraphs (a) through (f) of this section are exempt from classification as fissile material and from the fissile material package standards of 10 CFR 71.55 and 71.59, but are subject to all other requirements of this part, except as noted.

(a) Individual package containing 2 grams or less fissile material.

(b) Individual or bulk packaging containing 15 grams or less of fissile material provided the package has at least 200 grams of solid nonfissile material for every gram of fissile material. Lead, beryllium, graphite, and hydrogenous material enriched in deuterium may be present in the package but must not be included in determining the required mass for solid nonfissile material.

(c)(1) Low concentrations of solid fissile material commingled with solid nonfissile material, provided that:

(i) There is at least 2000 grams of solid nonfissile material for every gram of fissile material, and

(ii) There is no more than 180 grams of fissile material distributed within 360 kg of contiguous nonfissile material.

(2) Lead, beryllium, graphite, and hydrogenous material enriched in deuterium may be present in the package but must not be included in determining the required mass of solid nonfissile material.

(d) Uranium enriched in uranium-235 to a maximum of 1 percent by weight, and with total plutonium and uranium-233 content of up to 1 percent of the mass of uranium-235, provided that the mass of any beryllium, graphite, and hydrogenous material enriched in deuterium constitutes less than 5 percent of the uranium mass, and that the fissile material is distributed homogeneously and does not form a lattice arrangement within the package.

(e) Liquid solutions of uranyl nitrate enriched in uranium-235 to a maximum of 2 percent by mass, with a total plutonium and uranium-233 content not exceeding 0.002 percent of the mass of uranium, and with a minimum nitrogen to uranium atomic ratio (N/U) of 2. The material must be contained in at least a DOT Type A package.

(f) Packages containing, individually, a total plutonium mass of not more than 1000 grams, of which not more than 20 percent by mass may consist of plutonium-239, plutonium-241, or any combination of these radionuclides.

The grout and FBSR waste forms are exempt per paragraph (c). There is significantly more than 2,000 grams of solid nonfissile material for every gram of fissile material in grout and FBSR packages regardless of the package size.

The only paragraph that is applicable to liquids is paragraph (a). Per this paragraph, the total mass of fissile isotopes ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu must be 2 grams or less in a package with radioactive liquids. The calculations for the feed vectors SP9 1B and Early Start with off-site disposal until 2020 were done to determine if the volume of liquids in a package must be limited to be exempt. In these calculations, the total mass of ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu was calculated for each month in the corresponding feed vectors, and the monthly volume required to meet the 2 gram per package criterion was determined. Figure H-6 shows the acceptable volumes for SP9 1B and Early Start feed vectors. The acceptable volume that falls within 1,000 gal to 3,000 gal represents 67% (SP9 1B) and 50% (Early Start). A small number can be transported in 5,000-gal containers.

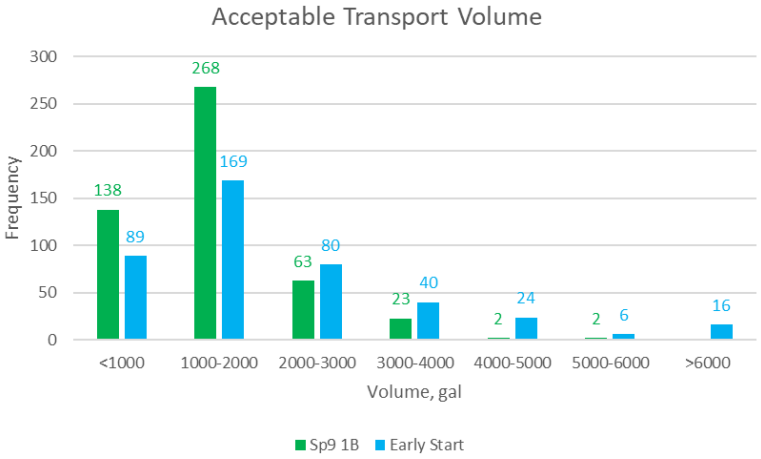


Figure H-6. Liquid Volumes Meeting Nonfissile Exempt for Liquids

There is no limitation on the quantity of solid materials that meet LSA-II requirements for solids in a conveyance (Table 5 in 49 CFR 173.427). Consequently, the quantity of grout and FBSR waste forms is only limited by the monthly availability of these waste forms and possibly by the number of railcars in the dedicated train. However, a quantity limitation exists for liquids that meet LSA-II requirements for liquids. The maximum quantity in conveyance must not exceed 100 A_2.

The monthly number of containers with liquids per conveyance was calculated from the A_2 content of the liquid volume meeting the nonfissile exempt and 100 A_2 limits. Figure H-7 shows the monthly number of containers per conveyance for SP9 1B and Early Start feed vectors.

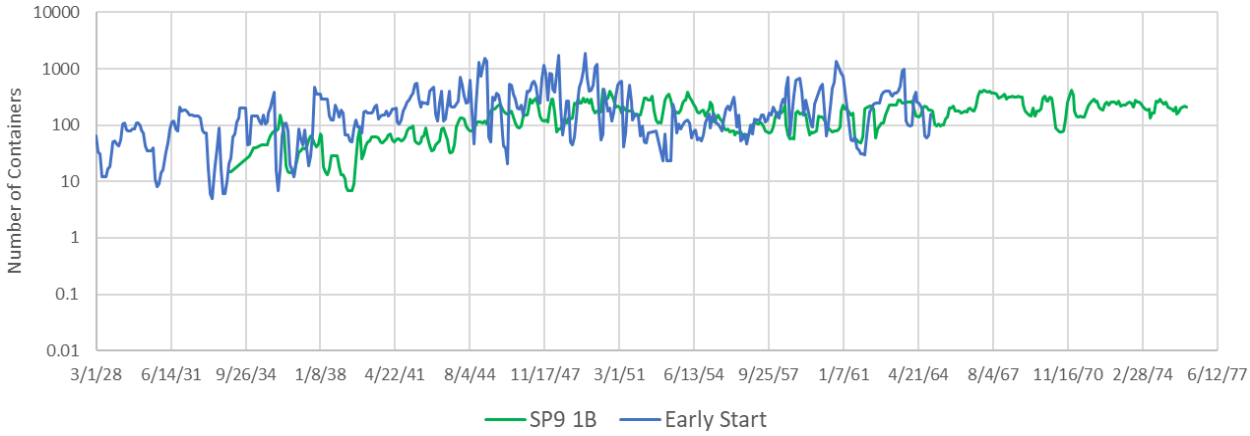


Figure H-7. Number of Containers with Liquids per Conveyance

Figure H-8 presents the same information in the form of a histogram. Based on Figure H-8, 95% (SP9 1B) and 92% (Early Start) of the trains can carry 25 or more containers with liquids without exceeding the 100 A_2 limit for LSA shipments. Only 5% (SP9 1B) and 8% (Early Start) of the trains will have to carry less than 25 containers. Consequently, the A_2 requirement has a small impact on the number of containers in a conveyance. The majority of trains can transport 50 containers with liquids or more.

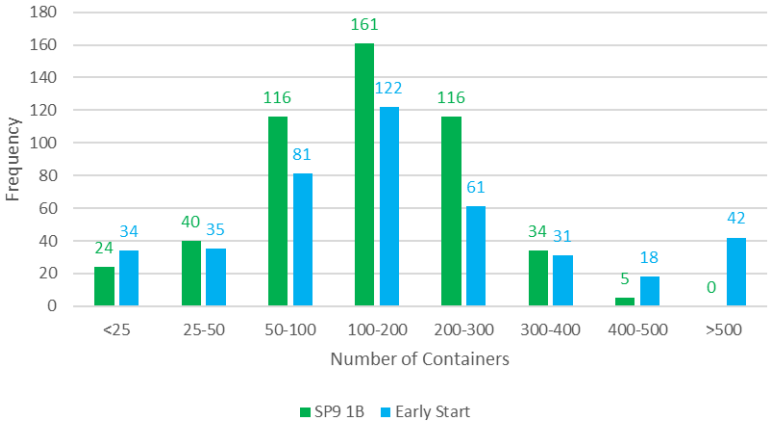


Figure H-8. Number of Containers per Conveyance

Figure H-9 and Figure H-10 show the annual liquid volumes generated in feed vectors SP9 1B and Early Start. The average annual volumes are 1.3 Mgal (SP9 1B) and 2.6 Mgal (Early Start). The liquid waste treatment capacity, whether at an independent vendor facility, or at Clive or WCS, should be sufficient to process the corresponding annual volumes. The existing licenses at Clive and WCS would need to be amended if larger waste volumes need to be treated.

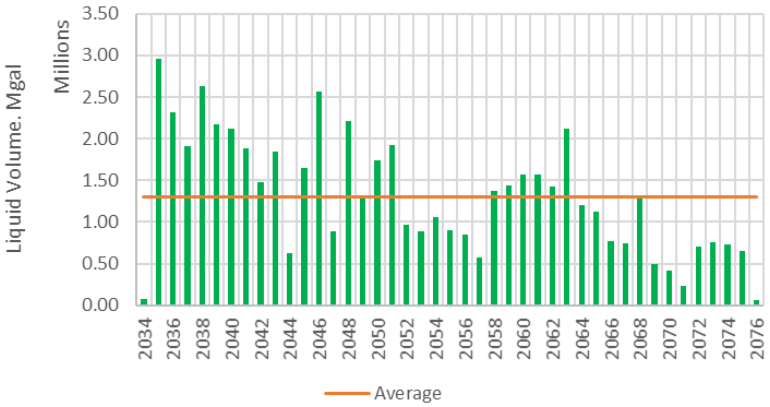


Figure H-9. SP9 1B Feed Vector Annual Liquid Volumes

H.5.3 External Dose Rates

Other criteria for LSA-II (applicable to both solids and liquids) are the external dose rate requirements.

10 CFR 71.47 states:

(a) Except as provided in paragraph (b) of this section, each package of radioactive materials offered for transportation must be designed and prepared for shipment so that under conditions normally incident to transportation the ***radiation level does not exceed 2 mSv/h (200 mrem/h)*** *at any point on the external surface of the package, and* ***the transport index does not exceed 10****.*

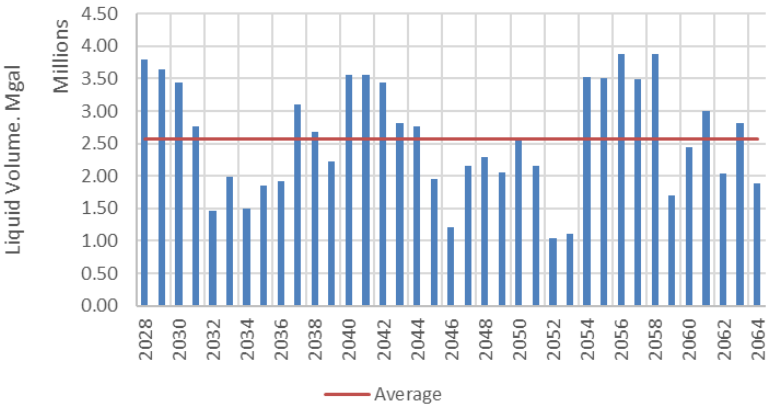


Figure H-10. Early Start Feed Vector Annual Liquid Volumes

(b) A package that exceeds the radiation level limits specified in paragraph (a) of this section must be transported by exclusive use shipment only, and the radiation levels for such shipment must not exceed the following during transportation:

(1) 2 mSv/h (200 mrem/h) on the external surface of the package, unless the following conditions are met, in which case the limit is 10 mSv/h (1000 mrem/h):

(i) The shipment is made in a closed transport vehicle

(ii) The package is secured within the vehicle so that its position remains fixed during transportation, and

(iii) There are no loading or unloading operations between the beginning and end of the transportation.

Consequently, if the radiation level does not exceed 2 mSv/h (200 mrem/h) at any point on the external surface of the package, and the transport index does not exceed 10, no other dose requirements apply. The transportation index of 10 means that the highest dose rate 1 m from the source shield is 10 mrem/hr.

Figure H-11 shows the total monthly activity of the liquid and grout waste forms for the SP9 1B and Early Start feed vectors and the total monthly activity of the FBSR waste form for the SP9 1B feed vector. The total monthly activities of the grout and FBSR are lower than the total monthly activities of liquids because the radionuclide concentrations are diluted when the grout and FBSR waste forms are generated. Consequently, if liquids meet the external dose rate requirements, then the grout and FBSR waste form will also meet them. In addition to the lower activities, grout and FBSR are self-shielding, which leads to the doses decreasing further.

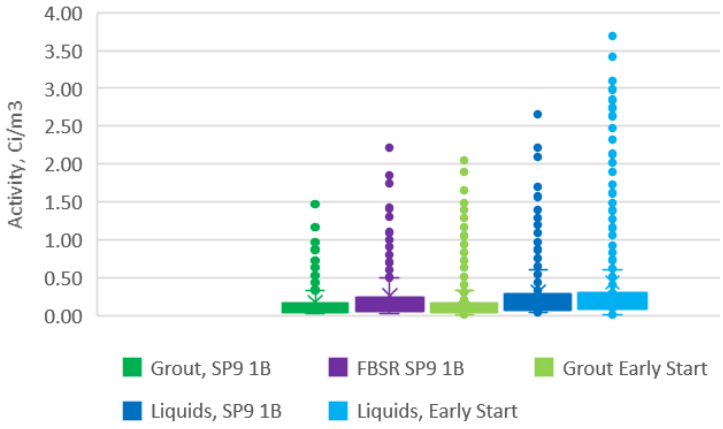


Figure H-11. Total Monthly Activity of the Liquid, Grout and Fluidized Bed Steam Reforming Waste Forms

The dose rates were calculated using MicroShield® Version 11.26.[4] This software is licensed to Sandia National Laboratories (SNL) and available through the SNL network software distribution.

The calculations were done for a 5,000-gal ISO tank with radioactive liquids (ISO tank details are provided in Section H.7.1). The ISO tank consists of an outer and inner cylinder (Figure H-12) made of steel. The outer cylinder is 2.4 m (8 ft) in diameter and 6 m (20 ft) long, with a wall thickness of 0.25 cm (0.1 in). The inner cylinder is 1.8 m (6 ft-10 in.) in diameter and 5.5 m (18 ft) long, with a wall thickness of 0.95 cm (⅜ in.). A 17.8 cm (7-in.) air gap is between the sides of the inner and outer cylinders, and a 30.5 cm (12-in.) air gap is between the ends of the outer and inner cylinders. The inner cylinder is filled with liquid and has the volume of 18,181 L (4,803 gal).

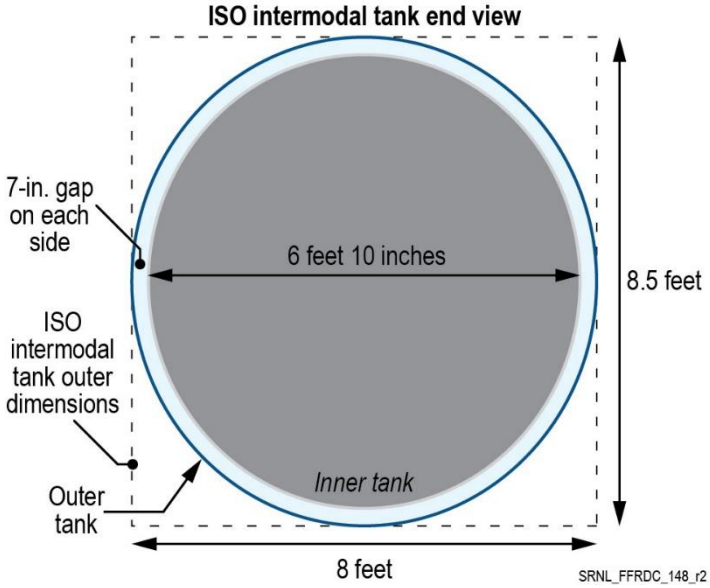


Figure H-12. ISO Tank Schematic

[4] MicroShield is a registered trademark of Grove Software, a Division of Grove Engineering, Inc., Lynchburg, Virginia.

Figure H-13 shows the geometry used in MicroShield. A "Cylinder Volume – Side Shields" geometry was used to represent the sides of the ISO tank (Figure H-13 left). A "Cylinder Volume – End Shields" geometry was used to represent the ends of the ISO tank (Figure H-13 right). Two representations were required because the air gap between the cylinder sides is different from the air gap between the cylinder ends. The dose rates were calculated at four locations shown in Figure H-13:

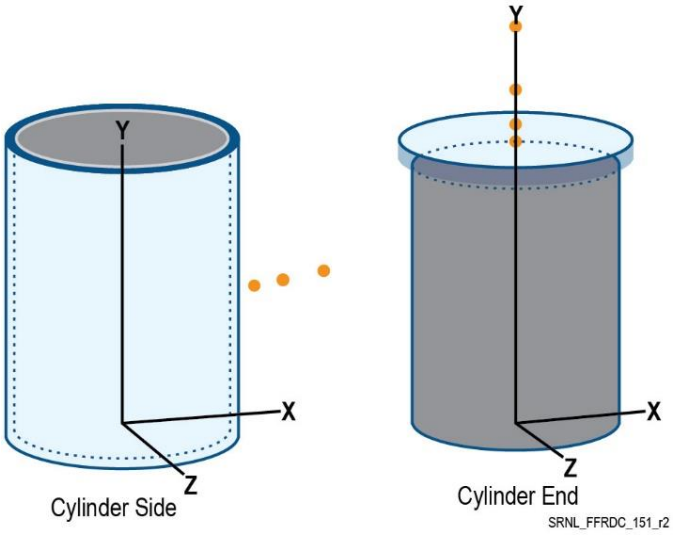


Figure H-13. ISO Container Geometry in MicroShield

- **On contact**. Note that this distance was set equal to 5 cm (2 in.) for survey meter geometry considerations. The contact dose rate limit is 200 mrem/hr.
- **At 30 cm (~1 ft) from the surface**. Note that this dose rate is not required for transportation; the dose rate is required for determining whether the waste can be disposed of as a bulk waste. The 30 cm (~1 ft) dose limit is 100 mrem/hr.
- **At 1 m**. This dose rate is also known as the transportation index (TI); the TI limit is 10 mrem/hr.
- **At 2 m**. This dose rate is commonly used in transportation risk assessment software (e.g., RADTRAN).

The steel cylinder walls were modeled in MicroShield using iron with a density of 7.86 g/cm^3. The density of liquids was set equal to the average density of 1.30 g/cm^3 (SP9 1B feed vector) and 1.34 g/cm^3 (Early Start feed vector).

The radionuclide source in curies of each radionuclide in the ISO tank (internal cylinder) was defined for the SP9 1B and Early Start feed vectors. The maximum concentration of each radionuclide in the feed vector was used, except for the ^{137}Cs concentration in the Early Start feed vector that was defined at the 94th percentile; the reason is illustrated in Figure H-14. The cumulative probability distribution of ^{137}Cs in the Early Start feed vector has a very long tail resulting in high ^{137}Cs concentrations in a small portion of the feed vector. The liquid volume in the tank was assumed to be 5,000 gal. The actual liquid volume is slightly smaller (4,803 gal), and the tank is filled to 95–98% of its capacity. In addition, to meet nonfissile material exemptions, the transported liquid volumes will be 4,000 gal or less, as discussed previously.

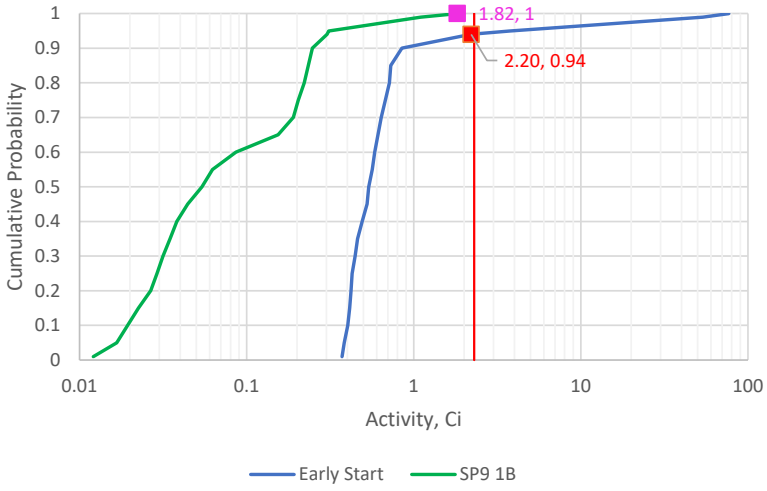


Figure H-14. Cumulative Probability of Cesium-137 Activity in 5,000-Gallon ISO Tank

Figure H-15 and Figure H-16 show the calculated maximum external dose rates at four distances from the external surface of the 5,000-gal ISO tank filled with SP9 1B and Early Start feed vector liquids, respectively. These figures also show the dose rate limits at contact: at 30 cm and at 1 m. The calculated dose rates are below the corresponding limits in all the cases.

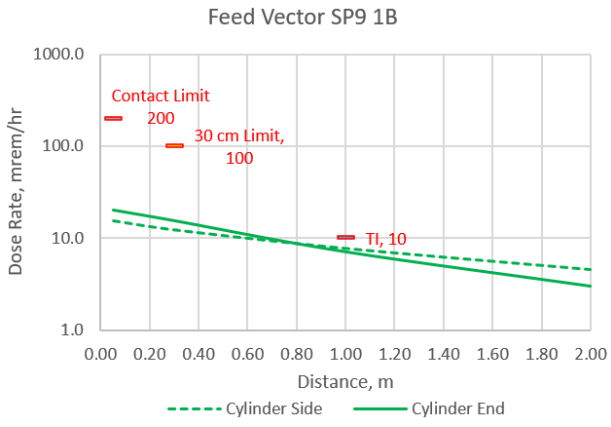


Figure H-15. Maximum External Dose Rates from a 5,000-Gallon ISO Tank with SP1 9B Feed Vector Liquids

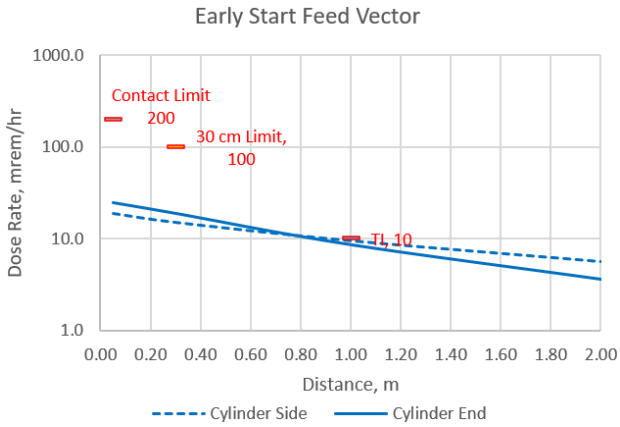


Figure H-16. Maximum External Dose Rates from a 5,000-Gallon ISO Tank with Early Start Feed Vector Liquids

The external dose rates are slightly higher in the cylinder end case at contact and 30 cm (~1 ft), and slightly lower at 1 m and 2 m (~3.25 ft and 6.5 ft) compared to the cylinder side case due to geometry. The results are summarized in Table H-2. Note that these dose rates include buildup, so the scattered photons are considered in the calculations.

Table H-2. Maximum External Dose Rates from a 5,000-Gallon ISO Tank with SP9 1B and Early Start Feed Vector Liquids

Feed Vector	Cylinder Geometry	Distance m	External Dose Rate mrem/hr
SP9 1B	Side	0.05	15.49
		0.30	12.37
		1.00	7.79
		2.00	4.60
	End	0.05	20.04
		0.30	15.37
		1.00	7.08
		2.00	3.01
Early Start	Side	0.05	18.88
		0.30	15.08
		1.00	9.50
		2.00	5.61
	End	0.05	24.43
		0.30	18.73
		1.00	8.62
		2.00	3.66

Additional runs were done with the reduced sets of radionuclides to identify the main contributors to the external dose rates. The results are shown in Figure H-17. The main contributor in both feed vectors is ^{137}Cs – 89% of the total external dose rate. The other contributors are ^{154}Eu (7%–9%) and ^{60}Co (1%–4%). The other radionuclides contribute less than 0.4% of the total external dose.

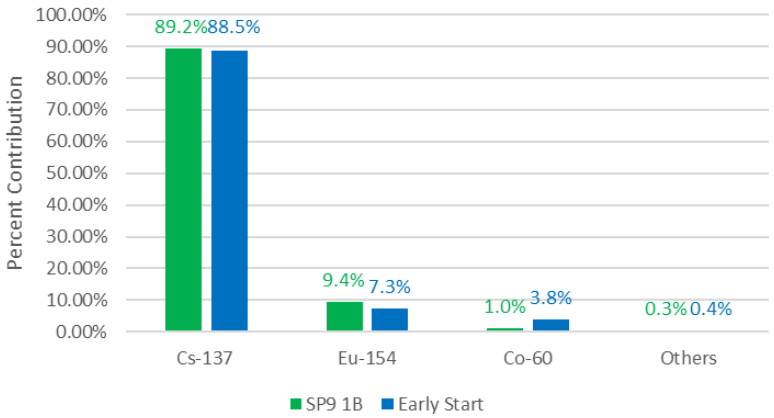


Figure H-17. Major Contributors to External Dose Rates from a 5,000-Gallon ISO Tank

The additional MicroShield runs were performed to identify the ^{137}Cs activity in the 5,000-gal tank that would result in exceeding the dose limit at 1 m from the ISO container using the Early Start feed vector maximum activity of ^{154}Eu and ^{60}Co. The calculated limiting concentration was 2.3 Ci of ^{137}Cs, which means that a small volume of Early Start feed vector would have to be transported in smaller than ISO containers. An example of a smaller (358–gal) container is shown in Figure H-18. This 10–gauge, 304 stainless steel container is 1.22 m wide × 1.1 m long × 1.19 m high (48 in. wide × 42 in. long × 47 in. high), with an estimated maximum safety fill depth of 1 m (41 in).

Figure H-18. 10-Gauge, 304 Stainless Steel Container

H.5.4 Radioactivity Distribution in the Waste Form

Another LSA-II criterion is that the radioactivity be uniformly distributed in the waste form. Because of the immobilization process, both grout and FBSR waste forms will meet this criterion.

For liquids, this criterion is satisfied with the assumption that the formation of solids containing radionuclides would not occur. Washington River Protection Solutions, LLC (WRPS) considered this requirement for the waste streams, which were evaluated against the probability that solids containing radiological constituents would precipitate from the liquid stream. The preliminary evaluation showed a very low probability of solids formation. This evaluation was considered applicable to the SP9 1B and Early Start liquid feed vectors. Current WRPS plans include testing the samples from Tank AP-106 in fiscal year (FY) 2023 to further evaluate the potential for precipitation.

H.5.5 Summary of the Low-Specific Activity Determination

In conclusion, the liquid, grout, and FBSR waste forms meet all of the requirements of LSA-II materials and are exempt from classification as fissile material. Consequently, liquid, grout, and FBSR waste forms can be transported in IP-2 or IP-3 packages. The proposed packaging is described in Section H.7.1.

One order of magnitude lower LSA-II limit for liquids compared to solids, along with an additional limit on A_2 quantity per conveyance for liquids, would result in equivalent consequences in a potential accident during transport.

H.6 RADIOLOGICAL WASTE ACCEPTANCE CRITERIA

As established in the previous section, the liquids, grout, and FBSR waste forms are exempt from classification as fissile material and meet all applicable LSA-II criteria. Consequently, liquid, grout, and FBSR can be transported offsite in IPs. Whether the waste forms can be accepted by the disposal facilities is determined based on the waste acceptance criteria.

H.6.1 Waste Acceptance Criteria

The radiological waste acceptance criteria for the Clive and WCS facilities are based on the NRC's classification system, which divides low-level waste (LLW) into "classes" for disposal, with Class A LLW being the least hazardous and Greater-than-Class C (GTCC) LLW being the most hazardous (Volume II, Appendix G, Section G.2). The NRC describes these classes in 10 CFR 61.55, "Waste Classification." The WCS is licensed for disposal of Class A, Class B, and Class C (as defined in 30 Texas Administrative Code [TAC] Section 336.362) LLW and mixed low-level waste (MLLW), and bulk Class A LLW and MLLW in reusable packages with dose rates of <100 mrem/hour at 30 cm (~1 ft). The Clive facility is licensed for disposal of Class A LLW and MLLW and bulk Class A LLW and MLLW in reusable packages with dose rates of <100 mrem/hour at 30 cm (~1 ft).

The dose rates at 30 cm (~1 ft) from the package calculated for the LAW liquids (Section H.5.3) are significantly below the 100 mrem/hr limit: 15.4 mrem/hr (SP9 1B feed vector) and 18.8 mrem/he (Early Start feed vector). The dose rates from the grout and FBSR packages are expected to be lower compared to liquids due to radionuclide dilution and self-shielding of grout and FBSR.

Two tables are provided by WCS for classifying wastes as Class A, B, or C for disposal; GTCC wastes are currently prohibited. The two tables from the WCS Federal Waste Facility (FWF) Generators Handbook (WCS, 2015) are inserted here as Table H-3 for long-lived nuclides and Table H-4 for short lived nuclides. The same two tables are provided by Clive for classifying wastes as Class A for disposal (Energy*Solutions*, 2015). Because the radiological waste acceptance criteria are identical at WCS and Clive, waste classified as Class A at Clive would be classified as Class A at WCS.

Table H-3. Table I Class A and C Waste – Long-Lived Isotopes

Radionuclide	Class A Limit		Class B Limit		Class C Limit	
^{14}C	0.8	Ci/m^3	[a]	Ci/m^3	8	Ci/m^3
^{14}C in activated metals	8	Ci/m^3	[a]	Ci/m^3	80	Ci/m^3
^{59}Ni in activated metals	22	Ci/m^3	[a]	Ci/m^3	220	Ci/m^3
^{94}Nb in activated metals	0.02	Ci/m^3	[a]	Ci/m^3	0.2	Ci/m^3
^{99}Tc	0.3	Ci/m^3	[a]	Ci/m^3	3	Ci/m^3
^{129}I	0.008	Ci/m^3	[a]	Ci/m^3	0.08	Ci/m^3
Alpha-emitting transuranic radionuclides with half-lives greater than 5 years	10	nCi/g	[a]	nCi/g	100	nCi/g
^{241}Pu	350	nCi/g	[a]	nCi/g	3,500	nCi/g
^{242}Cm	2,000	nCi/g	[a]	nCi/g	20,000	nCi/g
^{226}Ra[b]	10	nCi/g	[a]	nCi/g	100	nCi/g

Source: Table I of WCS, 2015, *Federal Waste Disposal Facility (FWF) Generator Handbook*, Rev. 4, Waste Control Specialists, LLC, Andrews, Texas.

[a] There are no limits established for these radionuclides in Class B wastes.

[b] This isotope is not listed in the classification tables in 10 CFR 61 but is required by the state of Texas to be included in classification determination.

Table H-4. Table II Class A, B and C Waste – Short-Lived Isotopes

Radionuclide	Class A Limit		Class B Limit		Class C Limit	
Total radionuclides with half-lives less than 5 years	700	Ci/m^3	[a]	Ci/m^3	[a]	Ci/m^3
^{3}H	40	Ci/m^3	[a]	Ci/m^3	[a]	Ci/m^3
^{60}Co	700	Ci/m^3	[a]	Ci/m^3	[a]	Ci/m^3
^{63}Ni	3.5	Ci/m^3	70	Ci/m^3	700	Ci/m^3
^{63}Ni in activated metals	35	Ci/m^3	700	Ci/m^3	7,000	Ci/m^3
^{90}Sr	0.04	Ci/m^3	150	Ci/m^3	7,000	Ci/m^3
^{137}Cs	1	Ci/m^3	44	Ci/m^3	4,600	Ci/m^3

Source: Table II of WCS, 2015, *Federal Waste Disposal Facility (FWF) Generator Handbook*, Rev. 4, Waste Control Specialists, LLC, Andrews, Texas.

[a] There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes. These wastes shall be Class B unless the concentrations of other radionuclides in Table II determine the waste to be Class C independent of these radionuclides.

Table I and Table II (reproduced as Table H-3 and Table H-4) are used to classify wastes as Class A, B, or C for disposal. Some points on the use of the tables:

- The specific activity of each nuclide in the final waste form must be known in Ci/m^3, except for transuranics and ^{226}Ra, which must be known in nCi/gram.
- Each limit is the full limit. For example, if ^{14}C is the only nuclide in the waste, and the concentration is 8 Ci/m^3, the waste would be classified as Class C; any other Table H-3 nuclide, or any additional amount of ^{14}C, would cause the waste to be GTCC.
- If there are multiple long-lived nuclides (Table H-3 nuclides), the fractional contribution of each nuclide must be calculated and the sum of those fractional contributions must be less than 1 for a given class of waste. The use of the sum of fractions to determine waste classification is explained in 10 CFR 61.55(a)(7).
- If a waste contains long-lived (Table H-3) nuclides AND short-lived (Table H-4) nuclides the waste form will be determined based on the classification of the long-lived (Table H-3) nuclides, unless a higher classification is derived from the short-lived (Table H-4) nuclides.

The diagram in Figure H-19 illustrates how the waste determination is performed. Note that only one path leads to Class A waste and only one path leads to Class B waste. These paths are shown with the dark red arrows. Multiple paths lead to Class C and GTCC waste. All grout and FBSR waste classified as Class C followed one path (shown with the dark red arrows). This path to Class C is related to long-lived radionuclides with the sum of fraction exceeding the long-lived limit for Class A waste. None of the grout and FBSR waste falls under GTCC.

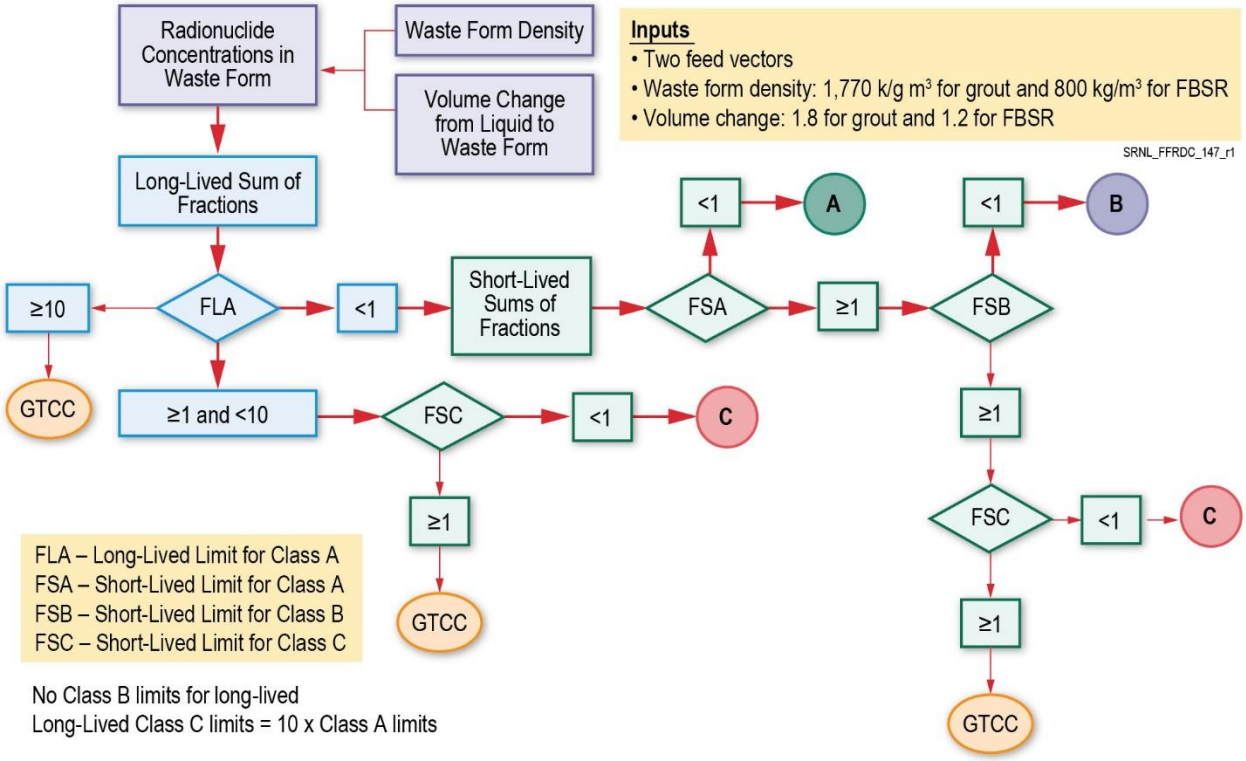


Figure H-19. Waste Class Determination Diagram

The calculations needed to classify the final waste forms for disposal can be illustrated using one long-lived nuclide. For this illustration, the SP9 1B feed vector data for July 2036 were chosen.

- Grouting will increase volume of the feed vector by a factor of 1.8, which will decrease specific activities found in the feed vector by a factor of 0.56 (= 1/1.8).
- The specific activity of ^{99}Tc in the feed vector is 2.18E-01 Ci/m^3 and therefore, specific activity of ^{99}Tc in the grout waste form will be 1.22E-01 Ci/m^3 (= 2.18E-01 × 0.56).
- The fractional activity of ^{99}Tc in grout for Table H-3 Class C classification is 4.07E-02, which is derived by dividing the specific activity of the ^{99}Tc in the waste (2.18E-01 Ci/m^3) by the Class C limit for ^{99}Tc (3 Ci/m^3).
- The fractional contribution of each Table H-3 long-lived nuclide can be calculated in this way. The fractional contribution of each nuclide is then summed. For the grout from July 2036, the sum of those fractions is 0.282. Because it is less than 1 but greater than 0.1, the grout produced in July 2036 will be Class C for long-lived nuclides.
- Because there are short-lived Table H-4 nuclides in the July 2036 feed, it is also necessary to calculate the classification of the short-lived nuclides using Table H-4 criteria, in the same manner as above. For the grout from July 2036, the sum of those fractions is 0.378 for the Class A limits. Because it is less than 1, the grout produced in July 2036 will be Class A for short-lived nuclides.
- Finally, the classification of the grout produced in July of 2036 can be determined based on the Table H-3 (long-lived) classification (Class C in this case), unless the Table H-4 (short-lived) classification is higher. In this example, because the Table H-4 (short-lived) classification is not higher than Class C, the final classification of the grout from July 2036 is Class C.

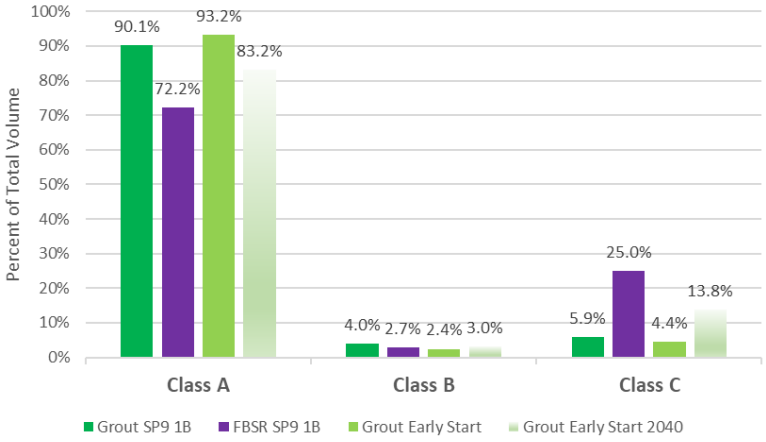
Information provided by the feed vectors, combined with information on the characteristics of the final waste forms, can be used to determine the classification (Class A, B, C, or GTCC) of the final waste form for each month that waste form is produced.

The SP9 1B and Early Start feed vector data were copied in an Excel file. The workbooks were setup to: (1) contain the WCS Table H-3 and Table H-4 radiological waste acceptance criteria for classifying wastes for disposal, (2) access the feed vector data from for every month of waste production, and (3) use the logic of calculating the sum of fractions and determining the waste classification (Class A, B, C, or GTCC) from Table H-3 and Table H-4 waste acceptance criteria.

The workbooks are also setup so that the feed vector concentrations can be modified to match the characteristics of the final waste form. For example, the workbook will decrease the specific activities of the radionuclides to account for the volume increase defined by the liquid to solid volume multipliers of 1.8 (grout) and 1.2 (FBSR) and uses the waste specific densities of 1,770 kg/m^3 (grout) and 800 kg/m^3 (FBSR) to calculate the concentration of transuranics as nCi/gram of waste.

The feed vector tracks nine alpha-emitting transuranic nuclides with half-lives greater than 5 years: ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{243}Cm and ^{244}Cm. In the workbook, the concentrations of these nine transuranic nuclides in the final waste form are summed and compared to the 100 nCi/gram limit for transuranics.

The calculations in the Excel file were used to classify all discrete sets of monthly feed vector data. Table H-5 and Figure H-20 present the categorization results. All waste forms were assumed to be disposed of offsite, except Grout Early Start 2040. Grout Early Start 2040 assumed that grout generated until 2040 will be disposed of offsite and grout generated after 2040 will be disposed of onsite. 83% to 93% of the grout is Class A in the SP9 1B and Early Start feed vectors. The percent of Class B waste in grout is very small – from 2% to 4%. The percent of Class C waste in grout is relatively small – from 4% to 14%. When only the time period up to 2040 is considered, the percent of Class A in grout waste form is smaller (83%) and the percent of Class C waste is higher. This is because the concentrations of long-lived radionuclides are higher during this time. Smaller dilution results in a smaller percent of the FBSR waste form being Class A waste (72%) and a higher percent being Class B (3%) and Class C (25%) waste compared to grout.



Note: "Grout Early Start 2040" assumed that grout generated until 2040 will be disposed of offsite and grout generated after 2040 will be disposed of onsite.

Figure H-20. Waste Form Classification Volume as a Percent of the Total Volume Designated for Off-Site Disposal

Table H-5 shows the number of months in which Classes A, B, and C are generated in two feed vectors for the grout and FBSR waste forms. Class A is generated during 82% to 94% of the total months. Class B is generated during 1% to 3% of the total months. Class C is generated during 4% to 17% of the total months.

Table H-5. Number of Months when Classes A, B, and C are Generated in Two Feed Vectors for the Grout and FBSR Waste Forms

Feed Vector	Total Volume (m^3)	Waste Form	Number of Months and Percent of Total Number of Waste Generation Months		
			Class A	Class B	Class C
SP9 1B[a]	382,946	Grout	466	9	21
			93.95%	1.81%	4.23%
SP9 1B[a]	255,297	FBSR	404	7	85
			81.45%	1.41%	17.14%
Early Start	650,580	Grout	393	10	21
			92.69%	2.36%	4.95%
Early start with off-site disposal until 2040	208,579	Grout	117	4	21
			82.39%	2.82%	14.79%

[a] SP9 1B refers to the System Plan Scenario 1B (ORP-11242, Rev. 9).

FBSR = fluidized bed steam reforming.

Figure H-21 to Figure H-24 show the calculated sum of fractions for the long-lived and short-lived radionuclides for each month of waste production for the four cases in Table H-5. In all grout cases, the Class B and C waste forms are produced only during the first 7 years of operations. Figure H-24 displays the sum of fractions in a different format to better show when Class B and Class C waste is generated during the first 12 years in the Early Start feed vector. In the FBSR case, the Class B and C waste forms are dominant during the first 10 years. After that, mostly Class A waste is generated.

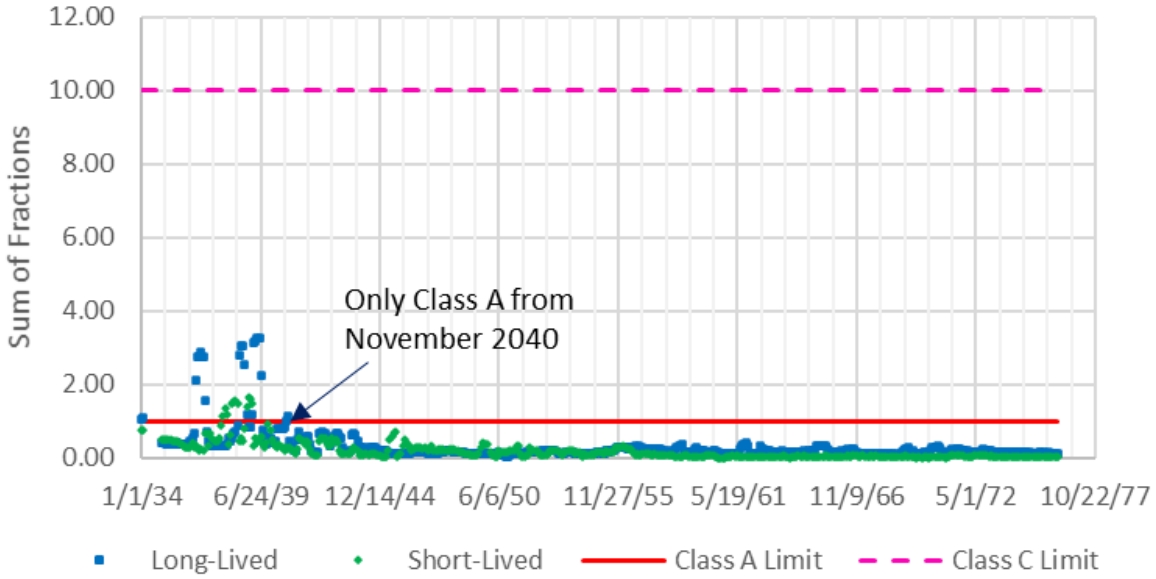


Figure H-21. Sum of Fractions for the Grout Waste Form, SP9 1B Feed Vector

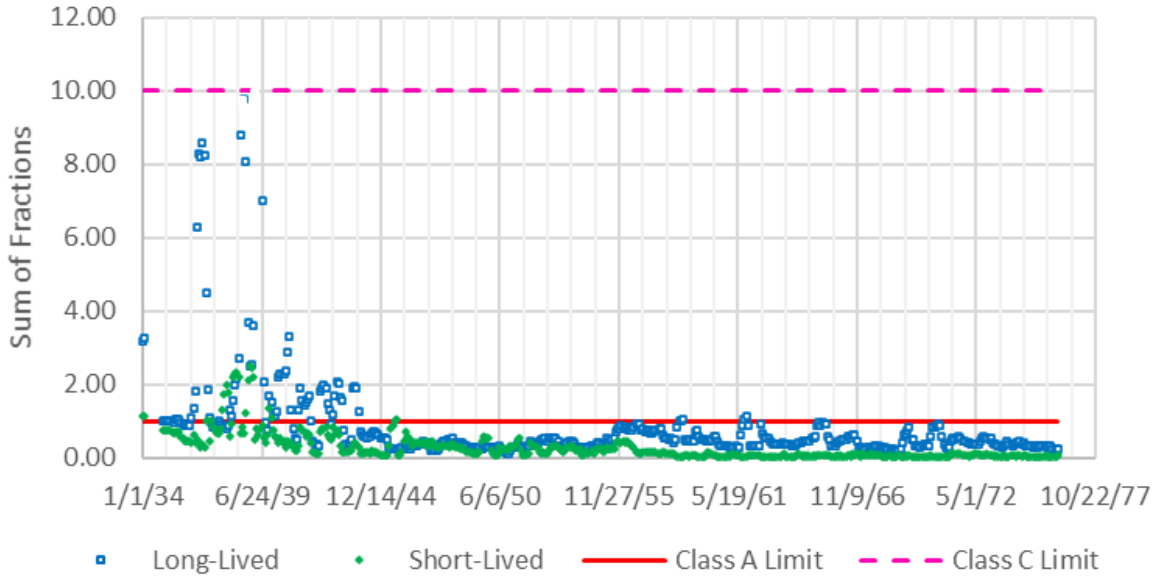


Figure H-22. Sum of Fractions for the Fluidized Bed Steam Reforming Waste Form, SP9 1B Feed Vector

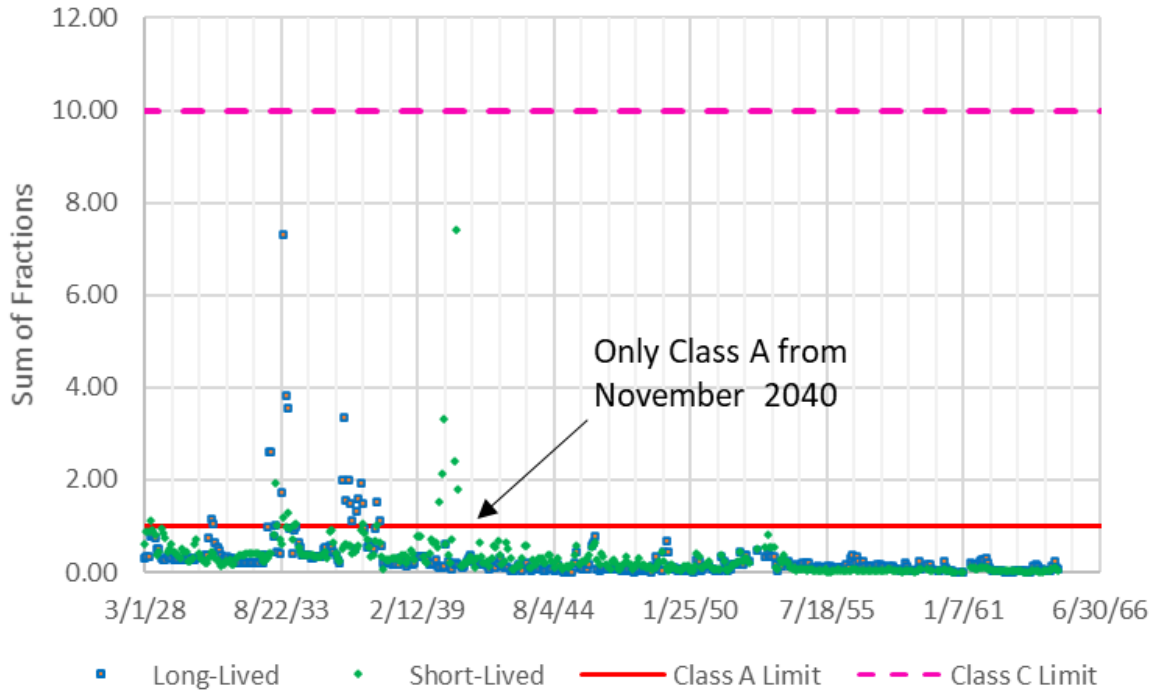


Figure H-23. Sum of Fractions for the Grout Waste Form, Early Start Feed Vector

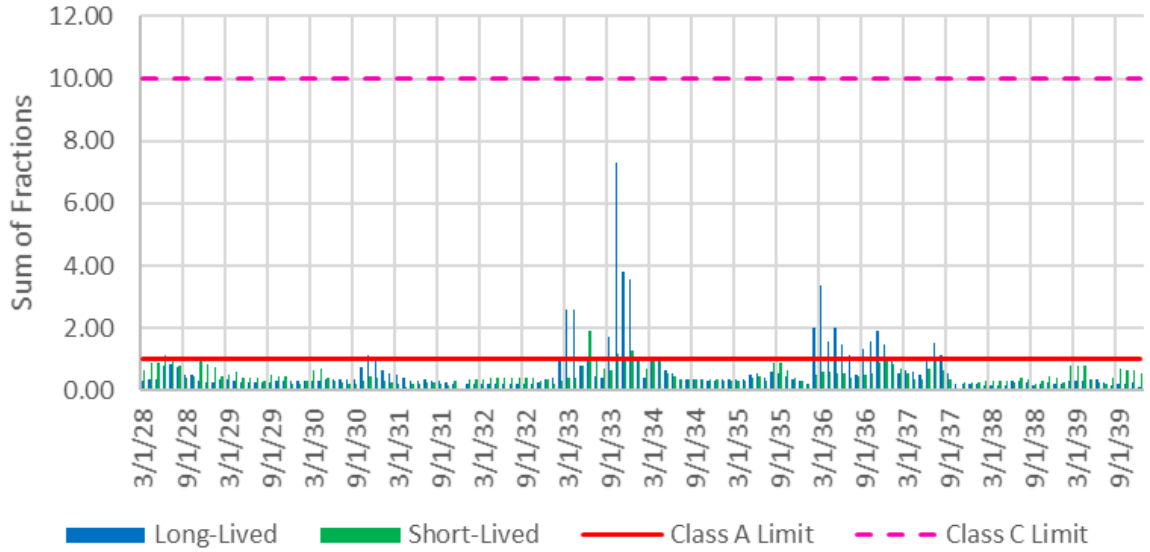


Figure H-24. Sum of Fractions for the Grout Waste Form, Early Start Feed Vector, Off-Site Disposal until 2040

H.6.2 Available Waste Disposal Volumes at Clive and Waste Control Specialists

Table H-6 provides the information on the grout and FBSR Class A and combined Class B and C waste volumes designated for off-site disposal. Class A waste can be disposed of at Clive and WCS. Class B and C can be disposed of only at WCS.

Table H-6. Waste Volumes Designated for Off-Site Disposal of Supplemental Low-Activity Waste

Feed Vector	Waste Form	Total Volume (m^3)	Clive and WCS	WCS
			Class A Volume (m^3)	Class B and C Volume (m^3)
SP9 1Ba	Grout	382,946	345,121	378,25
SP9 1Ba	FBSR	255,297	184,434	73,026
Early Start	Grout	650,580	606,030	44,551
Early Start with off-site disposal until 2040	Grout	208,579	173,453	35,126

[a] SP9 1B refers to the System Plan Scenario 1B (ORP-11242, Rev. 9).
FBSR = fluidized bed steam reforming. WCS = Waste Control Specialists, LLC.

The disposal volume available at the Class A West disposal cell at Clive is 2,293,665 m^3 (3 million yd^3) (Class A West is described in Volume II, Appendix G, Section G.2). Consequently, disposing of all Class A waste at Clive will take from 8% to 15% of the available disposal volume. Clive does not have a limit on the total activity. Figure H-25 compares the Class A volumes in alternatives Grout 4B and FBSR 1B (SP9 1B feed vector) and in Grout 6 (Early Start feed vector) to the total disposal volumes available at Clive and WCS. Note that alternative Grout 6 assumes off-site disposal until 2040. If for some reason on-site disposal is not possible and all grout generated in the Early Start feed vector needs to be disposed of offsite, only 26% of the available disposable volume would be needed at Clive (this alternative is not shown in Figure H-25).

The WCS waste acceptance criteria, Volume II, Appendix G, Section G.2.3), states that the total volume of the federal disposal cell is 736,238 m^3 (26 million ft^3), with a maximum allowable total volume of containerized waste of 229,366 m^3 (8.1E6 ft^3). Class B and C waste will be containerized, as will Class A waste with dose rates greater than 100 mrem/hr at 30 cm (~1 ft).

As discussed in Section H.6.1, the Class A LAW dose rate at 30 cm (~1 ft) is expected to be significantly below 100 mrem/hr and can be disposed of as a bulk waste. The Class B and C waste will take from 15% to 32% of the maximum allowable containerized volume. The space not taken by the Class B and C waste can be used for Class A waste. Disposing of all Class A waste at WCS will take from 25% to 49% of the available disposal volume.

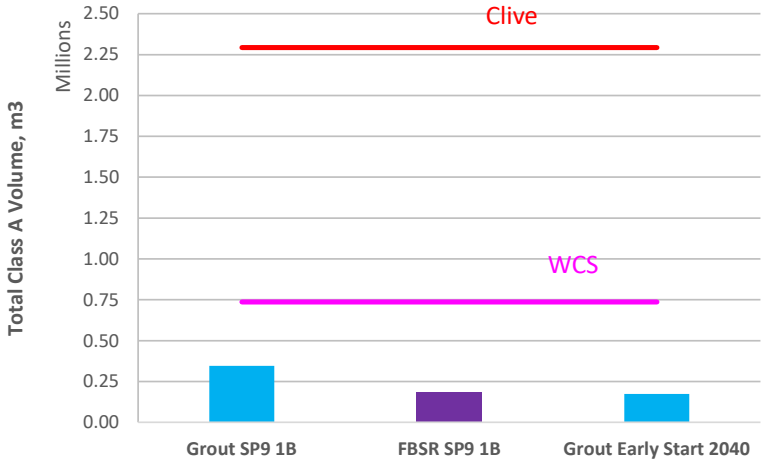


Figure H-25. Class A Volumes Compared to Clive and Waste Control Specialists Available Disposal Volumes

Figure H-26 compares the Class A and combined Class B and C volumes to the available disposal volumes, containerized and bulk, at WCS. Note that alternative Grout 6 assumes off-site disposal until 2040. If for some reason on-site disposal is not possible and all grout generated in the Early Start feed vector needs to be disposed of offsite, 88% of the available disposable volume would be needed at WCS (this alternative is not shown in Figure H-26).

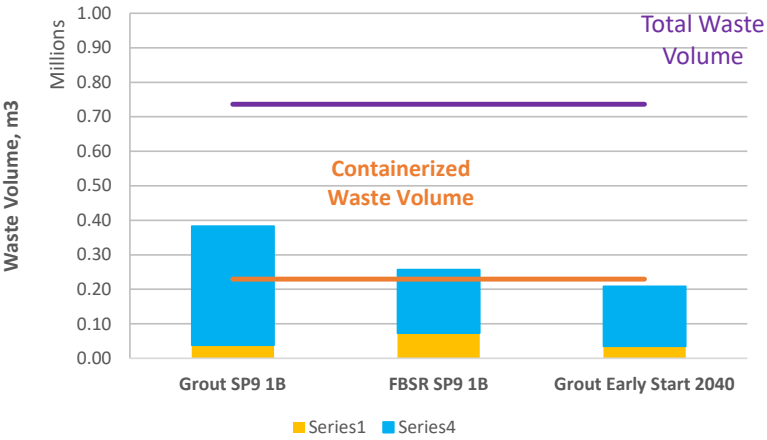


Figure H-26. Class A and Class B/C Volumes Compared to Waste Control Specialists Available Disposal Volumes

WCS has a limit on the total activity of 5.6E6 Ci. If all Class A, B, and C waste is disposed at WCS, the total activity will be from 3% (Early Start with off-site disposal until 2040) to 15.6% (SP9 1B) of the total activity limit.

Consequently, all grout and all FBSR waste forms can be disposed of offsite. All of the Class A grout and FBSR waste forms can be disposed of either at Clive or WCS, based on the available disposal volumes. All of the Class B and C grout and FBSR waste forms can be disposed of at WCS based on the available disposal volume and total activity. Note that for alternatives Grout 4B (Grout SP9 1B) and Grout 6 (Grout Early Start 2040), the volume of all Class A, Class B, and Class C waste will occupy only half of the total disposal volume at WCS. For alternative Grout 6, if on-site disposal becomes unavailable, all grout generated in this alternative can still be disposed of at WCS. Splitting the Class A waste form between the Clive and WCS facilities and how the split affects transportation and disposal costs are discussed in Section H.8.

H.7 OFF-SITE TRANSPORTATION

Two important conclusions were made in the previous sections. Section H.5 shows that all liquid, grout, and FBSR supplemental LAW forms are exempt from classification as fissile materials, meet the LSA-II requirements, and can be transported offsite in IPs. Section H.6 concludes that all of the Class A grout and FBSR waste forms can be disposed of either at Clive or WCS and that all Class B and C waste can be disposed of at WCS based on the Clive and WCS waste acceptance criteria, available disposal volumes, and total Ci limits (applicable only to WCS). This section discusses the waste packaging, transportation campaign schedule, and transportation routes.

H.7.1 Proposed Packaging

DOT requires that LSA materials be transported in packages meeting Type IP-1, Type IP-2 or Type IP-3 packaging criteria (49 CFR 173.411, "Industrial Packages"). In Table 6 of 49 CFR 173.427, DOT defines packaging requirements for all types of LSA materials, including the following requirements for LSA-II:

- LSA-II solid materials must be shipped in packages meeting Type IP-2 criteria for both "exclusive" and "non-exclusive" use shipments.
- LSA-II liquids must be shipped in packages meeting Type IP-2 criteria for "exclusive" and IP-3 criteria for "non-exclusive" use shipments.

Type IP-2 criteria in turn must meet the general design requirements of 49 CFR 173.410, and when subjected to the tests specified in 49 CFR 173.465(c) (free drop test) and (d) (stacking test) must prevent the (1) loss or dispersal of the radioactive contents, and (2) a significant increase in the radiation levels.

In the drop test, the package must be dropped on a flat horizontal unyielding surface. The drop height depends on the package mass and is defined in Table 10 of 49 CFR 173.465(c). The height is measured from the lowest point of the specimen to the upper surface of the target. Based on the weight of the proposed packages described below, the drop height would be 0.9 m (3 ft) (soft-sided bag with FBSR), 0.6 m (2 ft) (soft-sided bag with grout), and 0.3 m (1 ft) (ISO tank with liquids).

Note that 49 CFR 173.411(4) indicates that portable tanks (ISO) containers may be used for IP-2 or IP-3 provided they meet (i) through (iv), which do not include a drop test. Consequently, the ISO tanks for LSA-II liquids may not require the drop test.

One of the tests, the stacking test, requires that Type IP-2 packages must be able to sustain a compressive load equal to five times the maximum weight of the package for 24 hours without the loss or dispersal of the radioactive contents (49 CFR 173.465(d)).

Proposed Packaging for Liquids

A recommended container for liquid transport is a portable ISO tank. A portable tank may be used as a Type IP-2 or Type IP-3 package provided that the tank (49 CFR 173.411):

(i) Meets the requirements for Type IP-1 packages specified in paragraph (b)(1) (49 CFR 173.411)

(ii) Meets the requirements prescribed in ST/SG/AC.10, *Recommendations on the Transport of Dangerous Goods* (see 49 CFR 171.7, "Reference Material"), Chapter 6.7, "Requirements for the Design, Construction, Inspection and Testing of Portable Tanks and Multiple-Element Gas Containers (MEGCs)," or other requirements at least equivalent to those standards

(iii) Is capable of withstanding a test pressure of 265 kPa (38.4 psia)

(iv) Is designed so that any additional shielding that is provided must be capable of withstanding the static and dynamic stresses resulting from handling and routine conditions of transport and of preventing more than a 20% increase in the maximum radiation level at any external surface of the portable tanks.

The ISO tanks are common containers for transporting hazardous liquids, including corrosives, explosives, toxics, flammables, and radioactive. Figure H-27 shows ISO tanks with radioactive liquids arriving at Clive. The ISO tanks range from 4,000 gal to 6,000 gal. As discussed in Section H.5, the 4,000-gal containers would be most appropriate for the supplemental LAW liquids.

Source: Reproduced from a Clive brochure.

Figure H-27. ISO Containers with Radioactive Liquids Arriving at Clive (Utah)

An ISO tank consists of a cylindrical pressure vessel surrounded by a 6 m × 2.4 m × 2.6 m (20-ft × 8-ft × 8.6-ft) steel framework. ISO containers are built based on International Organization for Standardization (ISO) standards, are inspected and certified, and include a container safety certificate issued by the manufacturer. A liner or a protective coating is used inside the container. The right protective liner or coating allows a wide variety of reactive (corrosive) cargo to be shipped in the tank. ISO tanks are very reliable, can withstand extreme pressure and damage, and are capable of maintaining a specific temperature for temperature-sensitive cargo (i.e., precludes the precipitation of solids during transport).

The ISO containers are intermodal meaning that they can be transported by truck, by rail, and by ship. The liquids in ISO containers can be transported by trailer to an off-site vendor for grouting or by rail to an off-site disposal site for grouting and disposal. The liquids can be also transported by trailer to a railhead if needed. Using the same ISO containers for transport via trailer and rail provides additional operational flexibility and effectiveness. A 4,000-gal ISO container (with a maximum weight of 55,221 lb based on supplemental LAW liquid density) can be transported by a semi-tractor with a maximum loaded weight of 80,000 lb. The weight capacity of rail cars ranges from 140,000 to 220,000 lb, meaning that weight is not a limit for transport by rail.

Proposed Packaging for Solids

If the supplemental LAW liquids are converted to grout at a vendor facility, the grouted waste form will have to be transported to Clive and/or WCS for disposal. The IP-2 package proposed for transporting grout waste forms is an 8.4 m^3 (11 yd^3) soft-side container. The dimensions of each container will be 2.79 m long × 2.23 m wide × 1.35 m high (110 in. long × 88 in. wide × 53 in. high). To facilitate handling and to provide a rigid form for filling the soft-side containers with grout, the IP-2 soft side containers can be placed in shipping boxes that can be disassembled. The waste form would remain in the soft-side container and be emplaced as bulk waste if Class A at Clive and/or WCS or in a modular concrete canister (MCC) at WCS if Class B or C. Two 8.4 m^3 bags will fit into one MCC.

Similar packaging (e.g., shipping boxes and soft-sided bags) could potentially be used for the FBSR waste forms; however, additional confirmation may be required. The FBSR alternative was not one of the four selected alternatives evaluated in detail and because of this, the packaging required was not investigated at the same level of detail.

PacTec, Inc. is one manufacturer of the Type IP-2 LLW flexible containment packages (PacTec, 2022). These packages are designed, tested, and certified to Type IP-2 for soil, sand, gravel, and construction debris. These patented IP-2 flexible packages have passed all required tests under DOT 49 CFR 173.465, are suitable for use in the safe transport and disposal of radioactive materials, and offer cost savings over traditional metal containers and wooden boxes. The packages can be provided with an approved Certificate of Conformance. PacTec lifting frames support handling of their soft-sided packages.

Figure H-28 shows an example of a large soft-side container that can be used to ship LSA materials. The example is provided for illustration only and the shown bag dimensions are different from the 8.4 m^3 (11 yd^3) bag.

Source: PacTec, Inc. literature.

Figure H-28. Example of Soft Side Container for Shipping Low-Specific Activity Materials

Conceptually, the shipping box may be similar to the one shown in Figure H-29, but lighter in weight and have a shallower lid.

Source: Container Technologies Industries, LLC literature.

Figure H-29. Example of a Shipping Box Used for Solid Waste Transport

H.7.2 Transportation Campaign Schedule

Unit trains will likely be used to transport the supplemental LAW, whether in liquid or solid form (grout or FBSR). Unit trains can transport more than 90 rail cars of one type of freight in one car type for one destination, allowing rail cars to bypass intermediary rail yards and run directly from the origin to destination.

Liquid Waste Transport

As discussed in Section H.5, the volume of liquid waste that can be transported per month is restricted by the acceptable volume that meets the nonfissile material exemption. This volume varies from month to month and exceeds 4,000 gal only in a few months. Consequently, a 4,000-gal ISO container was recommended. The number of containers in a conveyance is limited to 100 A_2. The number of cars that can be shipped together because of this limit also varies from month to month. This information can be used to calculate the number of trains per month that are needed to transport liquids by rail. The transport by a trailer option is only limited by the volume of liquids per container because only one container is transported in a single conveyance.

The number of trains per month was calculated from the monthly feed vector liquid volume, acceptable container volume meeting nonfissile material classification, and the number of containers per conveyance meeting the 100 A_2 limit. Note that if the number of containers per train meeting the 100 A_2 limit was greater than 50, then 50 containers per train was assumed as a realistic number of containers in a dedicated train. Figure H-30 shows the monthly number of trains for the SP9 1B and Early Start feed vectors. The figure indicates that 4 months would require more than 30 trains, which is probably unrealistic and would most likely require lag storage of liquid wastes prior to transport.

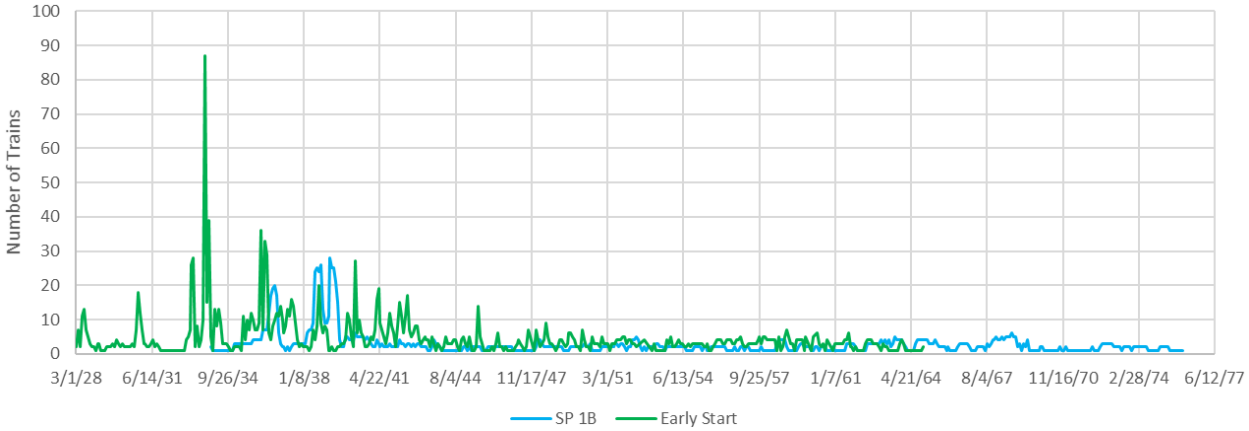


Figure H-30. Number of Trains per Month Required to Transport the Monthly Liquid Volumes

Figure H-31 presents the same information in a histogram. Based on the data presented in Figure H-30, in 93% (SP9 1B) and 79% (Early Start) of the cases, five trains or fewer per month will be required to transport the liquids. In 7% (SP9 1B) and 21% (Early Start) of the cases, more than five trains per month will be required.

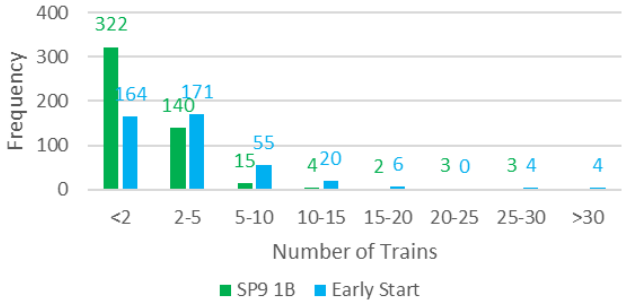


Figure H-31. Number of Trains per Months

Solid Waste Transport

If liquid supplemental LAW is converted to grout at the Hanford Site or a nearby vendor facility, or to FBSR at Hanford, the solid waste would have to be transported offsite. Rail is the most effective and economic transport option when the waste volumes are large.

The solid waste forms are commonly transported using gondola railcars. Figure H-32 shows a gondola car from the DOE Portsmouth site in Ohio being unloaded at WCS. Figure H-33 shows a high-sided gondola railcar from DOE O 435.1, *Radioactive Waste Management,* training material.

The gondola car cargo capacity is 90,910 kg (200,000 lb). The gondola car volume is 173 m^3 (226 yd^3). An 8.4 m^3 (11 yd^3) bag with grout weighs 14,868 kg (32,778 lb). Consequently, six bags can be transported by one gondola. An 8.4 m^3 bag with FBSR weighs 6,720 kg (14,815 lb). Consequently, 13 bags can be transported by one gondola. Note that the number of bags (either with grout or FBSR) is limited by the total weight, not by the total volume.

Figure H-32. Gondola Car from Portsmouth Site being Unloaded at Waste Control Specialists

Source: DOE O 435.1 training material.

Figure H-33. High-Sided Gondola Railcar

The number of gondolas per month required to transport the grout or FBSR waste forms was calculated from the monthly mass of grout and FBSR generated from the liquid feed SP9 1B and from the mass of grout generated from the Early Start liquid feed vector, assuming six soft-sided bags of grout or 13 soft-sided bags of FBSR per gondola. Figure H-34 shows the calculated number of gondolas in these three cases. The number of gondolas per month varies from 1 to 36 (grout SP9 1B), from 1 to 120 (grout Early Start), and from 1 to 11 (FBSR SP9 1B). Consequently, only one train per month carrying 90 gondola railcars would be required in all three cases, with the exception of a few months in grout Early Start.

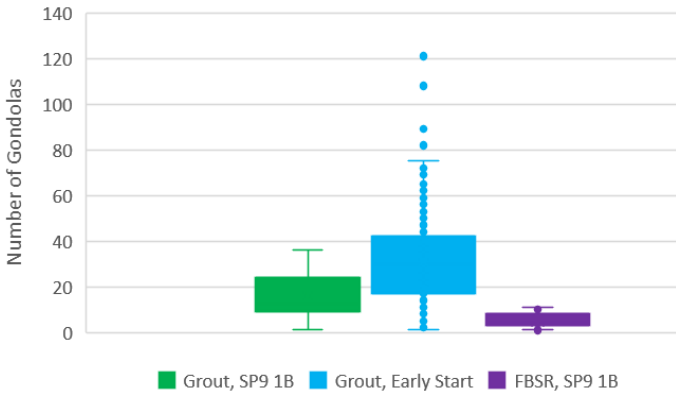


Figure H-34. Number of Gondola per Month Required to Transport Grout or Fluidized Bed Steam Reforming Waste Forms Offsite

If the transport of grout and FBSR is optimized to maintain 60 gondolas per train, then:

- The transport of a grout waste form produced either from the SP9 1B or Early Start feed vectors will require on average three trains per year with 60 gondolas.
- The transport of an FBSR waste form produced from the SP9 1B feed vector will require on average one train per year with 60 gondolas.

Note that other considerations such as on-site storage, disposal facility interim storage, and throughput may result either in more frequent or less frequent transport.

Figure H-35 compares the annual waste volume accepted at Clive from 2017–2021 to the mean annual volumes of grout and FBSR waste forms. Based on this comparison, accepting either grout or FBSR waste forms will not require an appreciable increase to the waste acceptance annual rates (note that the vertical scale in Figure H-35 is logarithmic).

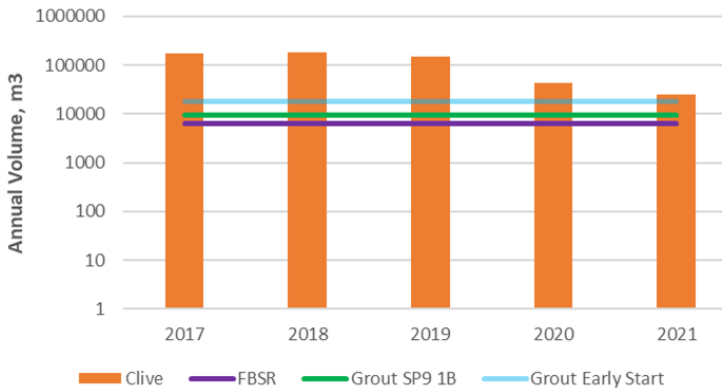


Figure H-35. Annual Waste Volume Accepted at Clive Compared to Mean Annual Volumes of Grout and Fluidized Bed Steam Reforming Waste Forms

H.7.3 Transportation Routes

Figure H-36 is a map of possible rail routes from the Hanford Site to WCS and to Clive. The rail routes shown in Figure H-36 were generated with WebTRAGIS, the Oak Ridge National Laboratory (ORNL) routing tool, assuming a dedicated train. WebTRAGIS was selected to comply with DOE O 460.2B, which states: "Ensure that proposed routes are analyzed using a transportation tool such as the Transportation Routing Analysis Geographic Information System (TRAGIS), the Stakeholder Tool for Assessing Radioactive Transportation (START), or another tool with equivalent capability. The route analysis tool must be capable of assessing and planning routes in accordance with relevant routing criteria of DOT regulations and any additional routing factors determined appropriate by DOE."

Figure H-36. Rail Routes from the Hanford Site to Waste Control Specialists (Texas) and Clive (Utah)

The route to WCS ends at the Eunice, New Mexico railnode. WCS will send their locomotive the short distance to Eunice, New Mexico, to bring the railcars to their facilities in Texas. The route to Clive ends at the Clive facility.

Using the default parameters for route selection in WebTRAGIS yields the route through Oregon, northern California, and Nevada for shipments from Hanford to Clive. When shipments are made, the shipping company and the railroads determine the actual route to use based on many considerations. One possible alternate route is shown through Idaho and Montana in Figure H-37. This route is 1,481 mi, which is slightly longer than the default route (1,213 mi). The analyses presented here are based on using the default WebTRAGIS route. The results based on the alternative route would be similar due to small variations in the route distance and population along the route. Similar alternate routes can also be identified for WCS.

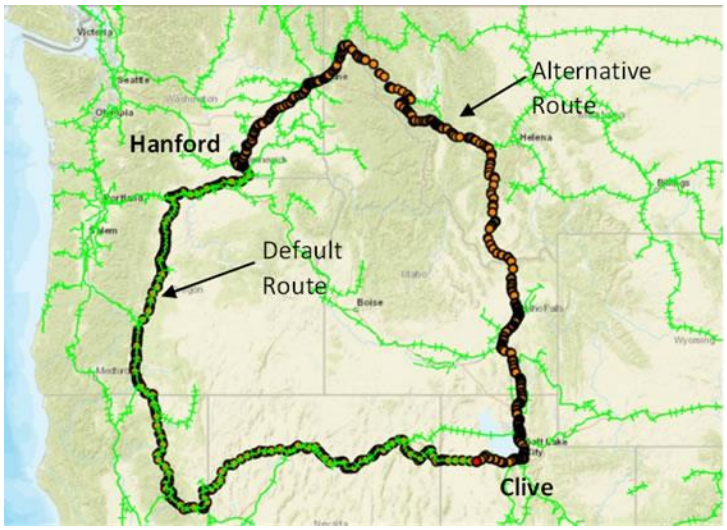


Figure H-37. Default and Alternative WebTRAGIS Routes from the Hanford Site to Clive, Utah

Table H-7 and Table H-8 summarize the route data for the default routes. Table H-9 provides a route comparison of the two WebTRAGIS default routes.

Table H-7. Route to Waste Control Specialists (Texas) Waste Disposal Facility Summary

State	Rural Population per mi²	Rural Distance mi	Suburban Population per mi²	Suburban Distance mi	Urban Population per mi²	Urban Distance mi
Colorado	24.6	325.3	1,228.7	100.86	5,336.1	17
Idaho	56.1	63.4	617.9	18.35	0	0
Montana	24.8	562.49	910.8	87.53	5,778.6	7.05
Nebraska	8.9	157.85	809.5	11.01	0	0
New Mexico	9.1	29.77	468.3	2.62	0	0
Oklahoma	21	41.82	280.6	0.99	0	0
South Dakota	13	47.8	253.4	1.09	0	0
Texas	20.4	495.28	976.7	110.66	4,414.3	7.01
Washington	22.6	130.86	1,429.2	48.41	4,674	6.32
Wyoming	15.8	209.55	1,142.9	19.43	3,462	0.54
Total	**21.83**	**2,064.12**	**1,060.37**	**400.95**	**5,110.92**	**37.92**

Table H-8. Route to Clive Disposal Facility (Utah) Summary

State	Rural Population per mi²	Rural Distance mi	Suburban Population per mi²	Suburban Distance mi	Urban Population per mi²	Urban Distance mi
California	10.6	266.71	411.4	7.86	0	0
Nevada	8.7	410.28	784.5	14.5	3,988	1.13
Oregon	21.7	275.71	756.7	40.28	4,968.1	3.57
Utah	2.4	48.06	997	1.13	0	0
Washington	10.7	118.99	1462.5	24.07	3,996.9	1.2
Average/Total	**12.30**	**1,119.75**	**926.89**	**87.84**	**4,582.85**	**5.90**

Table H-9. Route Comparison

Route Parameter	Route to WCS (Texas)	Route to Clive (Utah)
Total population, persons	1,779,152	341,089
Total distance, mi	2,502.99	1,213.49
Average speed, mi/hr	36	23
Number of states crossed	10	5
Number of rail companies	2	1
Number of large cities	5	3
Max population density, persons/mi^2	5,778.6	4,968.1
Average rural population density, persons/mi^2	21.8	12.3
Average suburban population density, persons/mi^2	1,060	927
Average urban population density, persons/mi^2	5,111	4,583
Total rural distance, mi	2,064.12	1,119.75
Total suburban distance, mi	400.95	87.84
Total urban distance, mi	37.92	5.9

WCS = Waste Control Specialists, LLC.

Figure H-38 and Figure H-39 compare the route average population densities and total distances in rural, suburban, and urban areas.

The data in Table H-7 and Table H-8 can be used to calculate the relative collective population dose to the people residing within the 800 m corridor on either side of the transportation route. The 800 m cutoff for exposed population was historically used in WASH-1238, *Environmental Survey of Transportation of Radioactive Materials to and from Nuclear Power Plants*, and in Radioactive Material Transport (RADTRAN) modeling applications. Retaining the 800 m value is overly conservative; however, it is done to provide comparability with older analyses.

The population densities along the route using the WebTRAGIS (Web-Based Transportation Routing Analysis Geographic Information System) model are based on the 2020 census. The population bins in WebTRAGIS are:

- Rural: Up to 139 persons/mi^2 (53.73 persons/km^2)
- Suburban: 139 to 3,326 persons/mi^2 (53.73 to 1,286 persons/km^2)
- Urban: More than 3,326 persons/mi^2 (more than 1,286 persons/km^2)

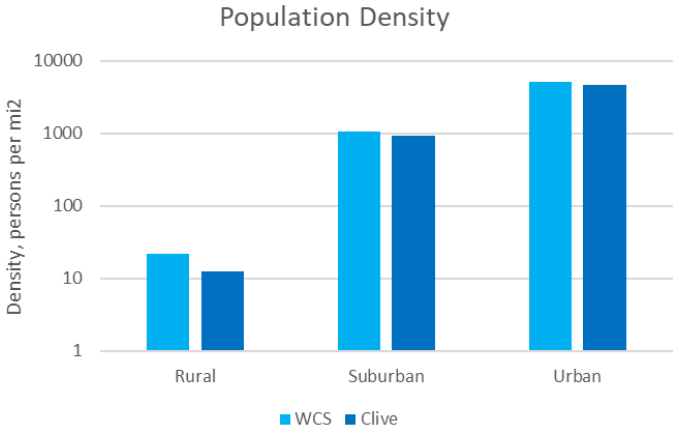


Figure H-38. Population Densities in Rural, Suburban, and Urban Areas

Figure H-39. Distances in Rural, Suburban, and Urban Areas

The population densities were not adjusted for the population increase from 2020 and for a future population increase. The comparison based on the 2020 population is adequate for the purpose of this simplified assessment. The external collective dose to residents $D_{off,p}$ (person-mrem) along the route segment (link) L from the shipment p (off link collective dose) is calculated as:

$$D_{off,p} = \frac{PD_L}{v_L} \cdot SF_L \cdot DIST_L \cdot URF_{off,p} \cdot TI_p = D_{rel,p} * URF_{off,p} \cdot TI_p \quad \text{(H-1)}$$

where

- PD_L is population density within 800 m corridor of the route segment L (persons/km^2)
- v_L is train average speed (km/hr)
- SF_L is shielding factor with default values of 1 (rural), 0.87 (suburban), and 0.018 (urban) links
- $DIST_L$ is link distance (km)
- $URF_{off,p}$ is off-link unit risk factor for shipment type p (km^2)
- TI_p is external dose rate at 1 m from the shipment surface or transportation index (TI), mrem/hour
- $D_{rel,p}$ is the relative population dose for shipment type p (person-hr/km^2).

The TI is the major parameter of Equation H-1 and represents the radiation dose rate at 1 m (3.3 ft) from the surface of the package. TI is a function of the waste density, radionuclide inventory, and self-shielding provided by the waste and by the package. As discussed in Section H.5, the TI of the ISO containers with the liquids and packages with grout or FBSR will meet the requirement of not exceeding 10 mrem/hr. The collective dose to residents along the route from shipment p is a sum of the collective doses of all the route segments. This dose is multiplied by the number of shipments p along the route to obtain the transportation campaign collective dose.

Because the package unit risk factors are not available, only relative population dose can be calculated. The unit risk factors can be calculated when the transportation risk analysis is done using RADTRAN or a similar transportation risk assessment software. To calculate the actual dose, the relative dose has to be multiplied by the package-specific TI and unit risk factor. For the purpose of the route comparison, the relative population dose is sufficient. The relative population doses per shipping of one soft-side container are 1.16E-05 (route to WCS) and 3.7E-06 (route to Clive), assuming TI × URF of 1E-05. The difference is due to the larger distance to WCS and higher population densities along the route.

H.8 COSTS

The off-site disposal costs include transportation and disposal costs. When the liquid feed is converted to grout offsite, there is also a cost of producing the grout. Note that transportation costs include insurance coverage for a nuclear incident and a precautionary evacuation, as defined by the Price-Anderson Amendments Act.

The total cost will depend on the split of the Class A waste between Clive and WCS. The total cost is calculated for no split cases (all Class A goes to Clive or to WCS) and for 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 fractions of Class A waste going to Clive. Rail shipping rates are confidential, and there are no "look-up tables" to assess the shipping costs. The rates provided by Perma-Fix Northwest, Inc. (Perma-Fix) for shipment to WCS were used, based on numerous prior rail shipments made by Perma-Fix. The rates are $14,000 per loaded gondola and $5,000 for return of the empty gondola. The average rail freight rate per ton-mile is $0.047 (Austin, 2015), with a standard deviation of $0.023. $14,000 per loaded gondola to WCS translates to $0.056/ton-mile, which is less than one standard deviation from the average. Because the distance to Clive is about 2× shorter, the cost of shipping a loaded gondola to Clive is assumed to be 2× less than the cost of shipping a loaded gondola to WCS.

The cost of the return shipment of an empty gondola is assumed to be the same. The rate of $0.056/ton-mile was used to calculate the cost per 4,000-gal ISO container filled with liquids. The cost of transporting an ISO container with liquids is $3,720 (WCS) and $1,860 (Clive). The cost of transporting an empty ISO container either to WCS or to Clive was assumed to be $1,328 (empty). The full-to-empty ISO container transportation cost ratio was assumed to be the same as a loaded-to-empty gondola transportation cost ratio for WCS.

The disposal cost of the bulk Class A waste at Clive is $886.99/yd^3 (Dempsey, 2022) or $1,160.14/m^3. The disposal cost of the bulk Class A waste and Class B and C waste at WCS are $1,460/m^3 and $7,830/m^3, respectively (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*). These costs were used in the calculations of the disposal costs.

The cost of off-site grout generation provided by Perma-Fix is $40/gal (Grondin, 2022). For the purpose of the cost estimate, an off-site vendor was assumed to offer grout generation at a similar cost. This cost was used as the rationale for setting the maximum grout generation cost to $45/gal of liquid treated. The cost of converting liquid into Class A grout and disposal of grout at Clive is $37.68/gal (Energy*Solutions*, 2019). Assuming the cost of disposal of Class A waste at Clive is about one-third of the total cost cited above, the cost of grouting is roughly $30/gal.

Finally, the cost of grout generation in GAO-17-306, *Opportunities Exist to Reduce Risks and Costs by Evaluating Different Waste Treatment Approaches at Hanford*, is $20/gal. Consequently, the calculations were done assuming $20, $30, and $45/gal of grout generation.

The results of the cost calculations are summarized in Table H-10 through Table H-12 and are plotted on the following pages in Figure H-40 to Figure H-42. In these calculations, the liquid feed is assumed to be converted to grout at a vendor facility and then transported to Clive and/or WCS for disposal. In addition to the total costs, the percent of the annual budget is also calculated, assuming an annual budget benchmark of $450 million. The total cost increase from the case when all Class A waste is disposed of at Clive, compared to the case when all Class A waste is disposed of at WCS, ranges from 3.8% to 7.9%. The total cost increase from the case when 50% of Class A waste is disposed of at Clive, compared to the case when all Class A waste is disposed of at WCS, ranges from 2.0% to 5.0%. Consequently, the cost is not a significant differentiator.

- The total cost ranges from $1.92 billion to $3.47 billion and represents 10.4% to 18.8% of the benchmark annual budget of $450 million when the SP9 1B feed vector liquid is converted to grout at a vendor facility and then transported to Clive and/or to WCS for disposal (alternative Grout 4B).
- The total cost ranges from $3.11 billion to $5.76 billion and represents 18.7% to 34.6% of the benchmark annual budget of $450 million when Early Start feed vector liquid is converted to grout at a vendor facility and then transported to Clive and/or to WCS for disposal (alternative Grout 6 in an unlikely situation in which on-site disposal becomes unavailable and all grout is disposed of offsite).
- The total cost ranges from $1.13 billion to $1.97 billion and represents 21.0% to 36.5% of the benchmark annual budget of $450 million when Early Start feed vector liquid is converted to grout at a vendor facility and then transported to Clive and/or to WCS for disposal until 2040. The percent of total cost is similar, while the total cost is lower because this is a 12-year campaign compared to a 37-year campaign in Early Start with all waste disposed of offsite.

Table H-10. Off-Site Grout Disposal Costs, SP9 1B Feed Vector, Grouting by a Vendor

Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$3,473,584,887	18.8%	$2,617,915,014	14.2%	$2,068,533,205	11.21%
0.1	$3,458,441,348	18.7%	$2,602,771,476	14.1%	$2,053,389,666	11.13%
0.2	$3,443,297,809	18.7%	$2,587,627,937	14.0%	$2,038,246,128	11.05%
0.3	$3,428,154,271	18.6%	$2,572,484,398	13.9%	$2,023,102,589	10.97%
0.4	$3,413,017,732	18.5%	$2,557,347,859	13.9%	$2,007,966,050	10.88%
0.5	$3,397,874,193	18.4%	$2,542,204,321	13.8%	$1,992,822,512	10.80%
0.6	$3,382,730,655	18.3%	$2,527,060,782	13.7%	$1,977,678,973	10.72%
0.7	$3,367,587,116	18.3%	$2,511,917,243	13.6%	$1,962,535,434	10.64%
0.8	$3,352,450,577	18.2%	$2,496,780,705	13.5%	$1,947,398,896	10.56%
0.9	$3,337,307,039	18.1%	$2,481,637,166	13.5%	$1,932,255,357	10.47%
1	$3,322,163,500	18.0%	$2,466,493,627	13.4%	$1,917,111,818	10.39%
Max increase	**4.36%**		**5.78%**		**7.32%**	

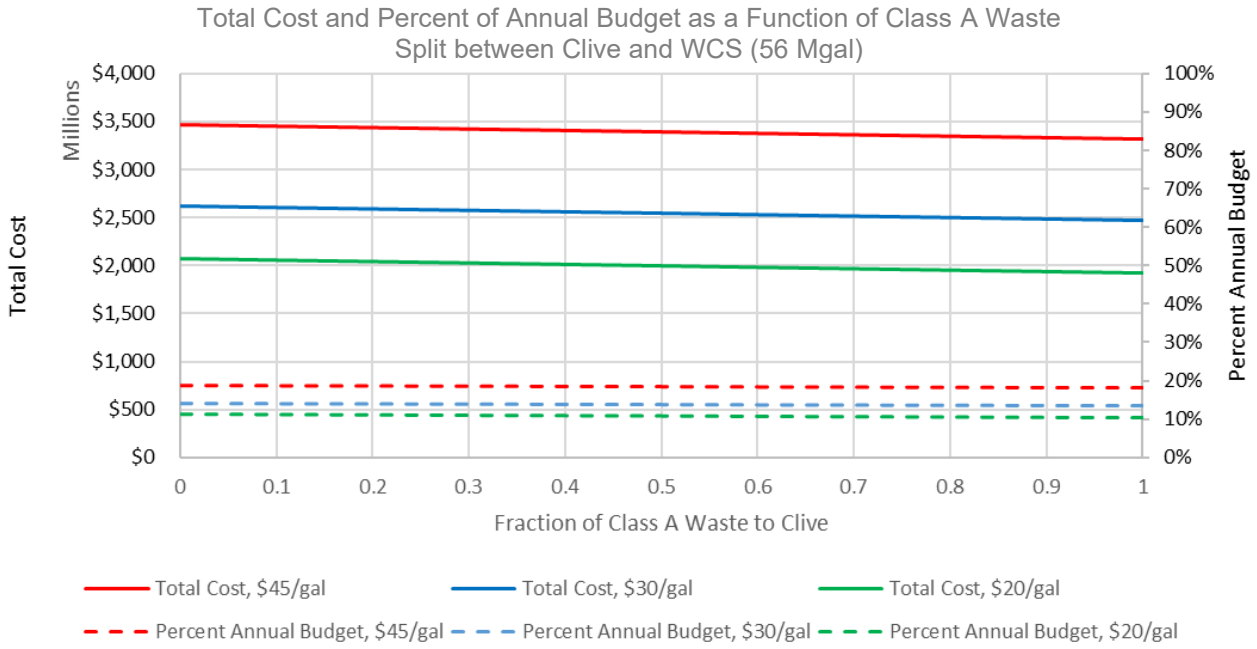
Table H-11. Off-Site Grout Disposal Costs, Early Start Feed Vector, Grouting by a Vendor

Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$5,760,813,526	34.6%	$4,310,836,837	25.9%	$3,379,881,053	20.30%
0.1	$5,734,306,379	34.4%	$4,284,329,689	25.7%	$3,353,373,906	20.14%
0.2	$5,707,768,231	34.3%	$4,257,791,542	25.6%	$3,326,835,758	19.98%
0.3	$5,681,261,083	34.1%	$4,231,284,394	25.4%	$3,300,328,611	19.82%
0.4	$5,654,722,936	34.0%	$4,204,746,247	25.3%	$3,273,790,463	19.66%
0.5	$5,628,203,788	33.8%	$4,178,227,099	25.1%	$3,247,271,316	19.50%
0.6	$5,601,696,641	33.6%	$4,151,719,952	24.9%	$3,220,764,168	19.34%
0.7	$5,575,158,493	33.5%	$4,125,181,804	24.8%	$3,194,226,020	19.18%
0.8	$5,548,639,346	33.3%	$4,098,662,656	24.6%	$3,167,706,873	19.03%
0.9	$5,522,132,198	33.2%	$4,072,155,509	24.5%	$3,141,199,725	18.87%
1	$5,495,594,050	33.0%	$4,045,617,361	24.3%	$3,114,661,578	18.71%
Max Increase	**4.60%**		**6.15%**		**7.85%**	

Table H-12. Off-Site Grout Disposal Costs, Early Start Feed Vector, Grouting by a Vendor, Off-Site Disposal until 2040

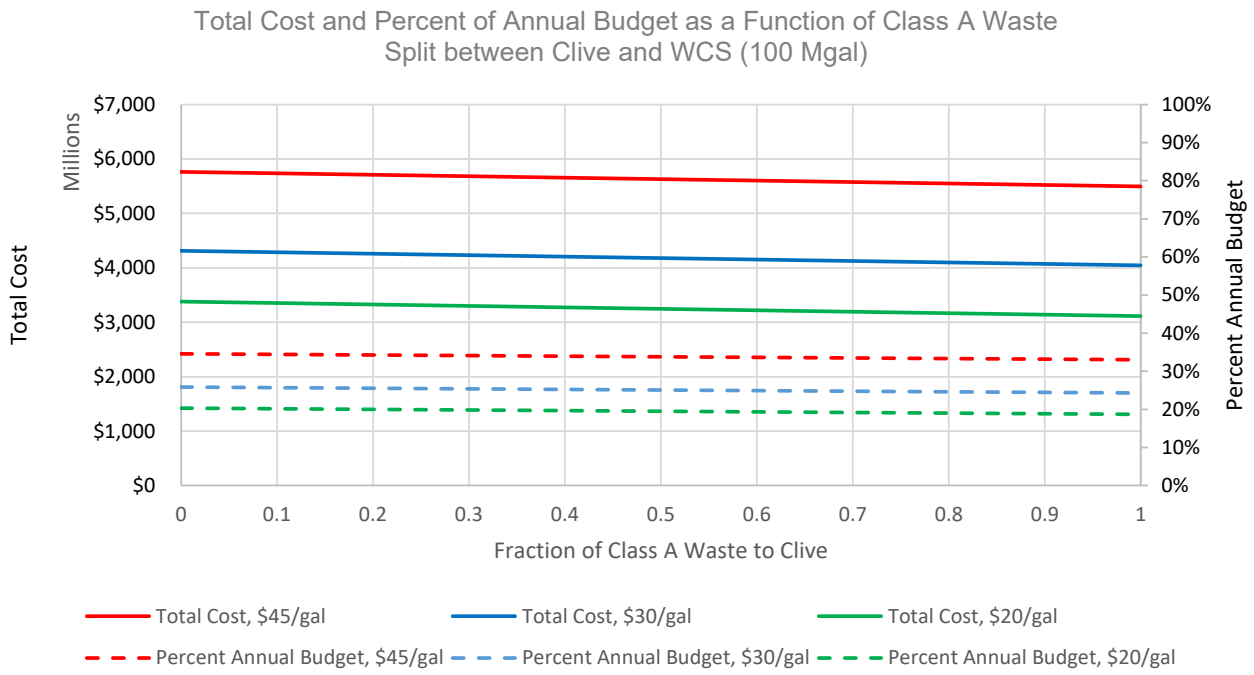
Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$1,968,654,218	36.5%	$1,506,303,160	27.9%	$1,209,451,221.71	22.40%
0.1	$1,961,119,385	36.3%	$1,498,768,328	27.8%	$1,201,916,388.96	22.26%
0.2	$1,953,553,553	36.2%	$1,491,202,495	27.6%	$1,194,350,556.21	22.12%
0.3	$1,946,018,720	36.0%	$1,483,667,662	27.5%	$1,186,815,723.46	21.98%
0.4	$1,938,452,887	35.9%	$1,476,101,829	27.3%	$1,179,249,890.71	21.84%
0.5	$1,930,918,054	35.8%	$1,468,566,997	27.2%	$1,171,715,057.96	21.70%
0.6	$1,923,371,222	35.6%	$1,461,020,164	27.1%	$1,164,168,225.21	21.56%
0.7	$1,915,805,389	35.5%	$1,453,454,331	26.9%	$1,156,602,392.46	21.42%
0.8	$1,908,270,556	35.3%	$1,445,919,498	26.8%	$1,149,067,559.71	21.28%
0.9	$1,900,704,723	35.2%	$1,438,353,666	26.6%	$1,141,501,726.96	21.14%
1	$1,893,169,891	35.1%	$1,430,818,833	26.5%	$1,133,966,894.20	21.00%
Max increase	**3.83%**		**5.01%**		**6.24%**	

Figure H-40 through Figure H-45 compare the transportation, disposal, and grout generation costs. The grout generation costs are the highest ones and the transportation costs are the lowest one. This explains why the total cost only slightly increases when all Class A grout is disposed of at WCS.



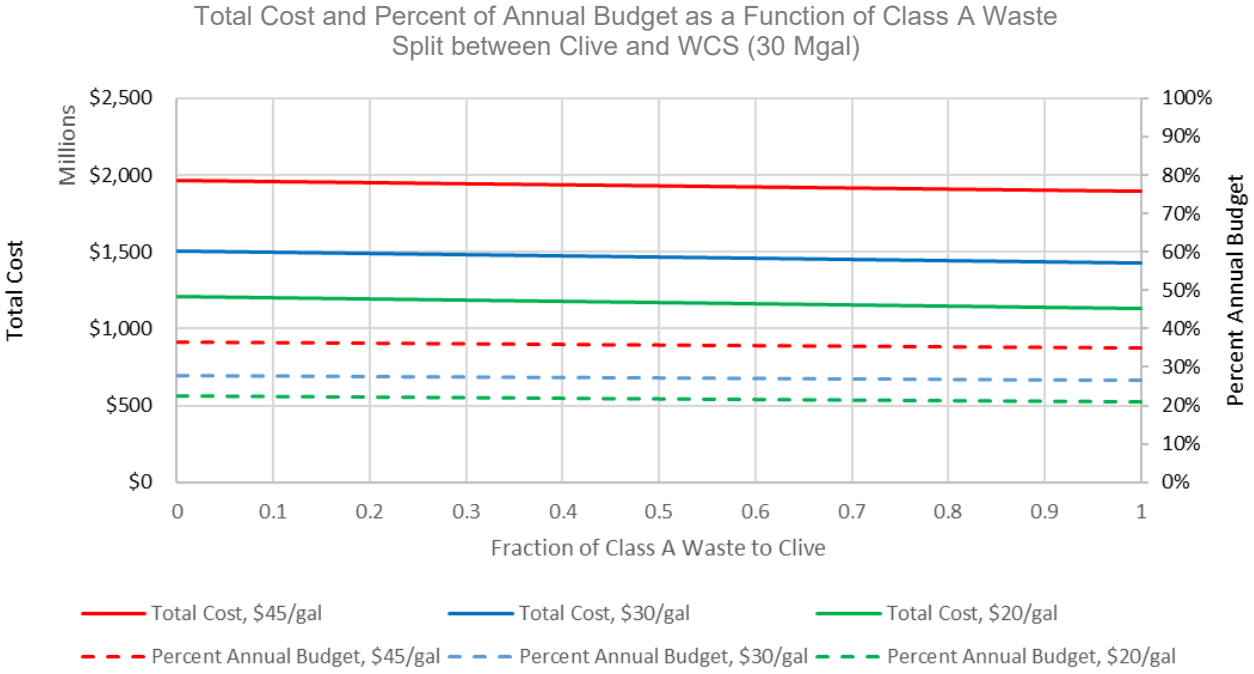
Note: 56 Mgal refers to the total volume of the liquid feed.

Figure H-40. Total Grout Disposal Cost and Percent Annual Budget, SP9 1B Feed Vector (Alternative Grout 4B)



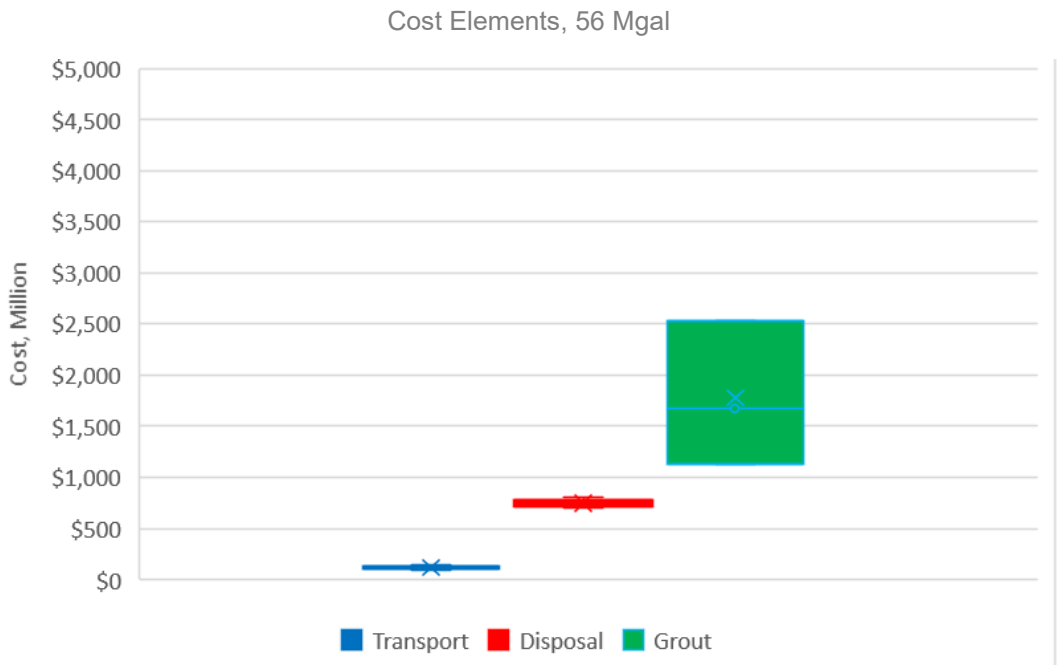
Note: 100 Mgal refers to the total volume of the liquid feed.

Figure H-41. Total Grout Disposal Cost and Percent Annual Budget, Early Start Feed Vector (Alternative Grout 6 with All Grout Disposed of Offsite)



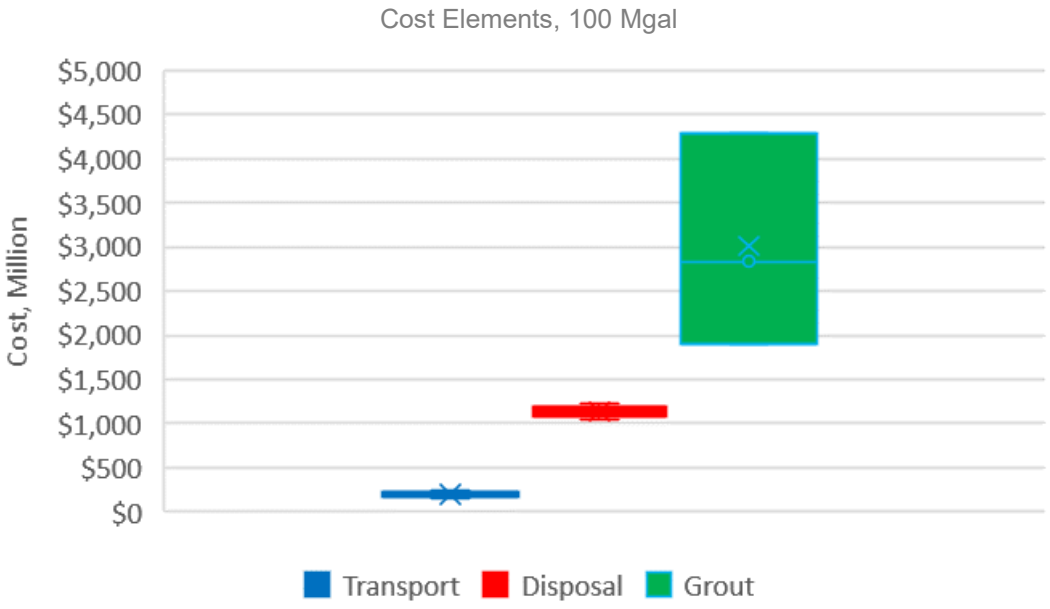
Note: 30 Mgal refers to the total volume of the liquid feed.

Figure H-42. Total Grout Disposal Cost and Percent Annual Budget, Early Start Feed Vector, Disposal until 2040 (Alternative Grout 6)



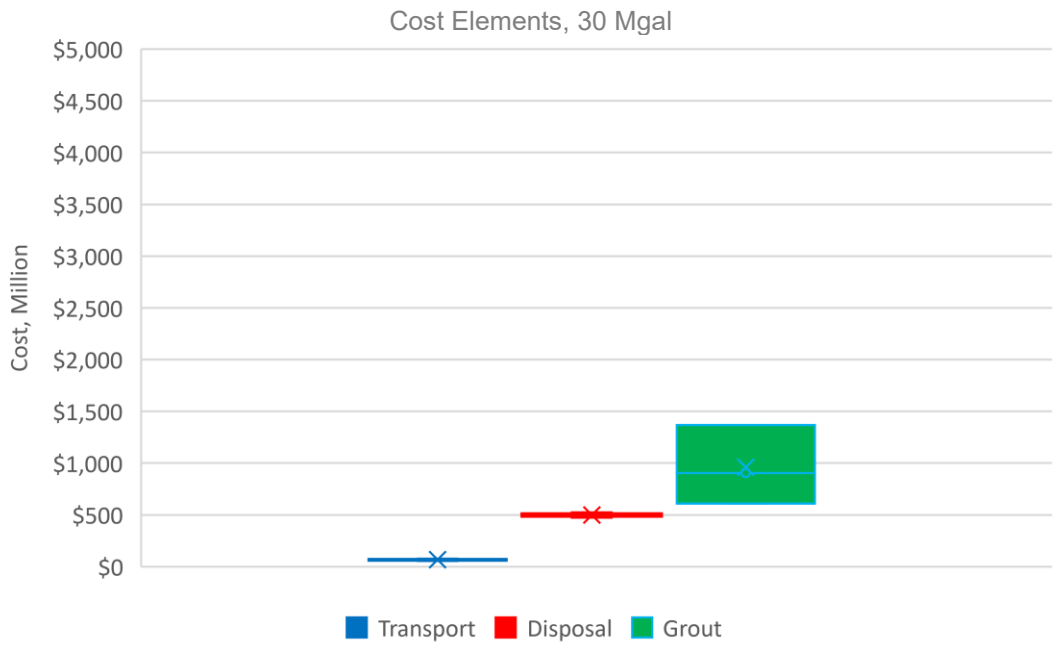
Note: 56 Mgal refers to the total volume of the liquid feed.

Figure H-43. Grout Disposal Cost Elements, SP9 1B Feed Vector (Alternative Grout 4B)



Note: 100 Mgal refers to the total volume of the liquid feed.

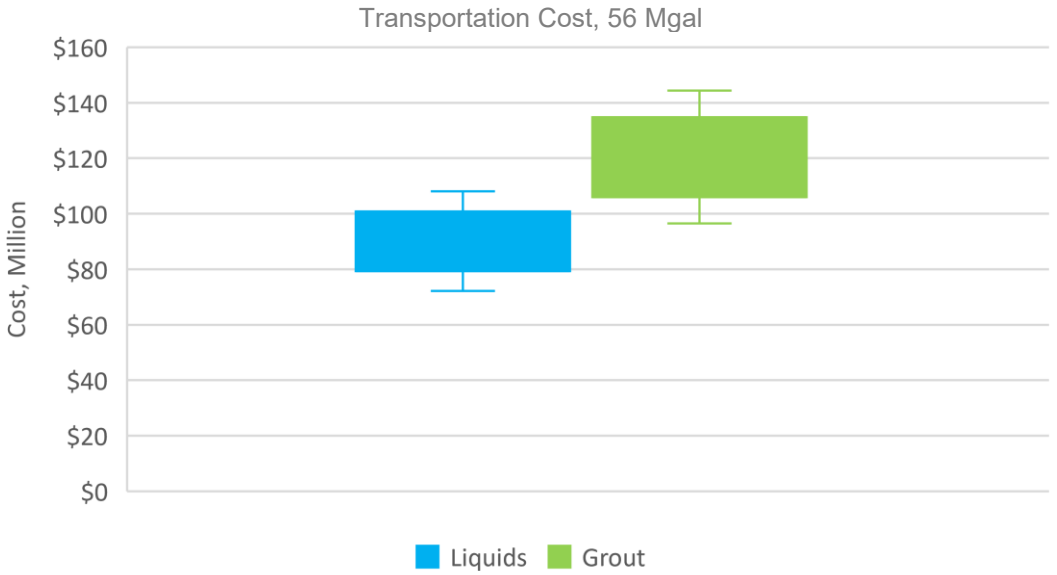
Figure H-44. Grout Disposal Cost Elements, Early Start Feed Vector (Alternative Grout 6 with All Grout Disposed of Offsite)



Note: 30 Mgal refers to the total volume of the liquid feed.

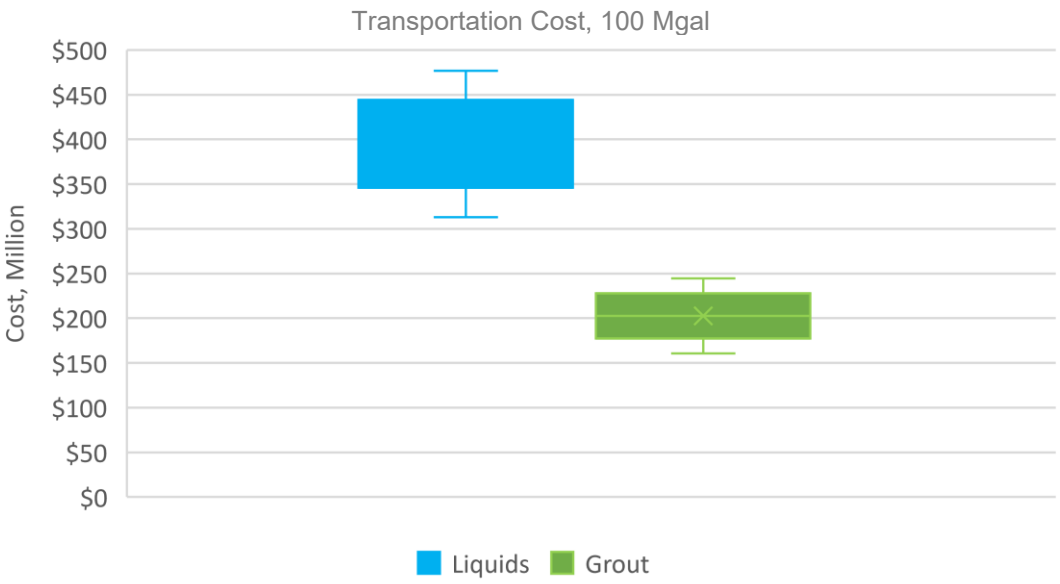
Figure H-45. Grout Disposal Cost Elements, Early Start Feed Vector, Off-Site Disposal until 2040 (Alternative Grout 6)

If the liquid feeds are converted to grout at Clive and/or WCS, the transportation costs will be different while the grout generation and disposal costs will be the same (as in Table H-10 through Table H-12). Figure H-46 through Figure H-48 compare the costs of transporting liquids and grout. The cost of transporting liquids is lower than grout in the SP9 1B feed vector, is noticeably higher in the Early Start feed vector, and is slightly higher in the Early Start feed vector with off-site disposal until 2040. This difference is because the number of ISO containers required is significantly larger in the Early Start feed vector compared to the SP9 1B feed vector. The difference in liquid transportation costs compared to grout will have minimal impact on the total cost because the transportation costs are a small fraction of the total costs.



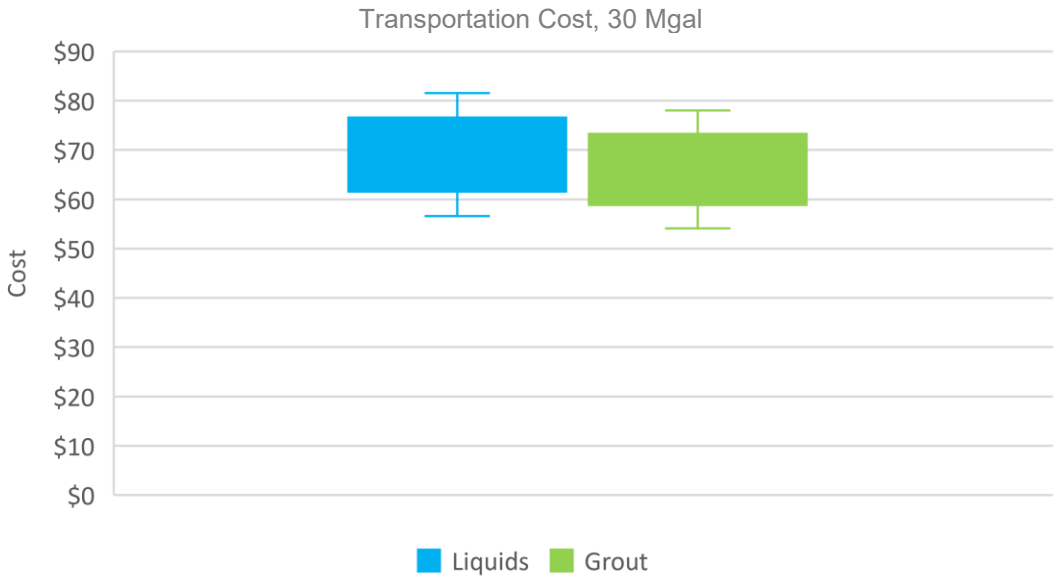
Note: 56 Mgal refers to the total volume of the liquid feed.

Figure H-46. Transportation Cost of Liquid and Grout, SP9 1B Feed Vector



Note: 100 Mgal refers to the total volume of the liquid feed.

Figure H-47. Transportation Cost of Liquid and Grout, Early Start Feed Vector



Note: 30 Mgal refers to the total volume of the liquid feed.

Figure H-48. Transportation Cost of Liquid and Grout, Early Start Feed Vector with Off-Site Disposal until 2040

Figure H-49 compares the total costs of off-site grout disposal. The lowest total cost is in the Early Start feed vector, with off-site disposal until 2040, alternative Grout 6. Next is the SP9 1B feed vector, alternative Grout 4B. The highest cost is in the Early Start feed vector. This case is considered to evaluate the costs in an unlikely situation in which on-site disposal becomes unavailable and all grout has to be disposed of offsite.

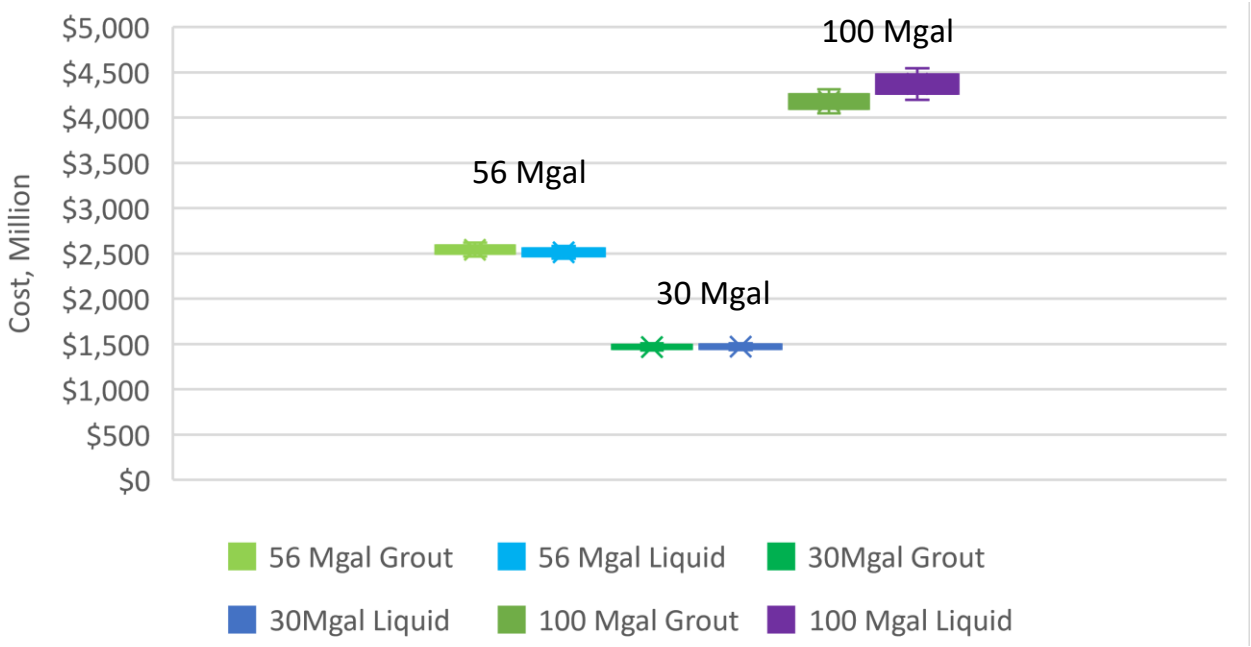


Figure H-49. Total Costs of Off-Site Grout Disposal

H.9 NONMONETARY CONSIDERATIONS RELATED TO TRANSPORTATION

The conclusion in the previous section is that the total off-site disposal cost only slightly increases with more Class A waste disposed of at WCS and less at Clive. The costs to transport liquids to Clive and/or WCS are only slightly different from the costs to transport grout to Clive and/or WCS, and the impact on total costs is minimal. This section considers nonmonetary factors as a function of the split of Class A waste between Clive and WCS.

Figure H-50 shows the total CO_2 emission as a function of the Class A split. In calculating the total CO_2 emission, 14.3 g of CO_2 is assumed to be produced per tonne-km of rail transport. This number is based on Tier 2 and Tier 3 locomotives. The mainline railroads (Class 1) are moving to Tier 4 locomotives, which have reduced emissions. Data on emissions can be found in the Association of American Railroads (AAR) annual facts report (AAR, 2020). The liquid feeds are assumed to be converted to grout at a vendor facility and then transported to Clive and/or WCS for off-site disposal. The FBSR waste form is generated at Hanford and then transported to Clive and/or WCS for off-site disposal. The smallest CO_2 emissions in grout cases are related to the Early Start feed vector with off-site disposal until 2040 (alternative Grout 6) due to the smaller mass of the transported grout. Note: If liquids are transported to Clive and/or WCS, the total CO_2 emissions will be 2.47 times smaller in all considered cases due to the smaller weight of liquids compared to grout.

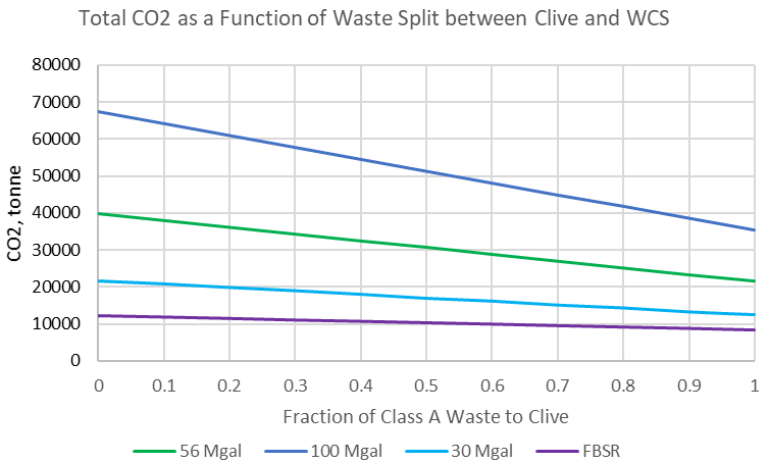


Figure H-50. Total CO_2 Generated During Transportation Campaign

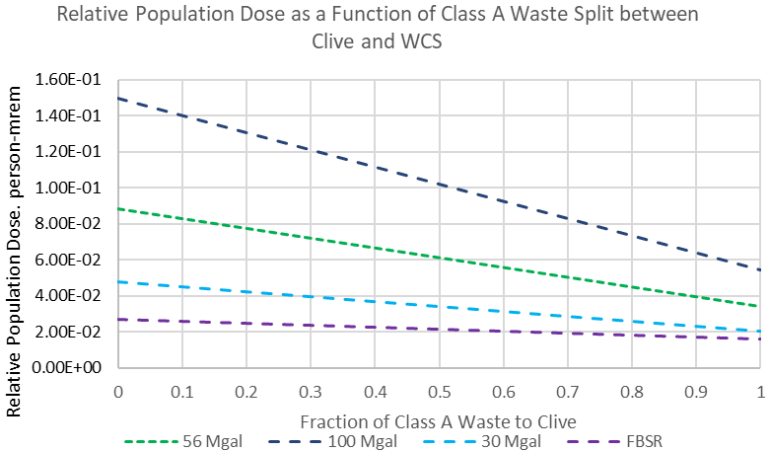


Figure H-51. Total Relative Population Dose During Transportation Campaign

Figure H-51 shows the relative total population dose to people residing along the transportation routes as a function of the Class A split. The total dose is relative because the relative population doses per one package were used in calculations, as described in Section H.7.3. The total dose decreases when the fraction of Class A waste disposed of at Clive increases because the route to Clive is shorter and the population density is lower. Note: If liquids are transported to Clive and/or WCS, the total dose will be 2.8 times higher (56 Mgal, Grout 4B) and 3.9 times higher (30 Mgal, Grout 6). This is because the number of ISO containers is larger compared to the number of grout bags.

Figure H-52 shows the total fatalities for the entire LAW supplemental treatment mission as a function of the Class A split. In calculating total fatalities, the freight train average accident rate of 1.17E-06 per mile was used (FRA, 2022). The average is for the period of time from 2013 to 2022. Figure H-53 shows the freight train accidents and fatality rates for this period of time.

The distance to the off-site facilities was multiplied by two, since the accident may happen when the train travels from Hanford to the disposal site or from the disposal site back to Hanford. The number of fatalities decreases when the fraction of Class A waste disposed of at Clive increases because the route to Clive is shorter. The fatalities range from 0.8 to 1.49, meaning that one fatality might be expected during the entire transportation campaign. Note: If liquids are transported to Clive and/or WCS, the number of fatalities will be 5.5 times higher (56 Mgal, Grout 4B) and 3.9 times higher (30 Mgal, Grout 6). This is because more trains will be required to transport liquids.

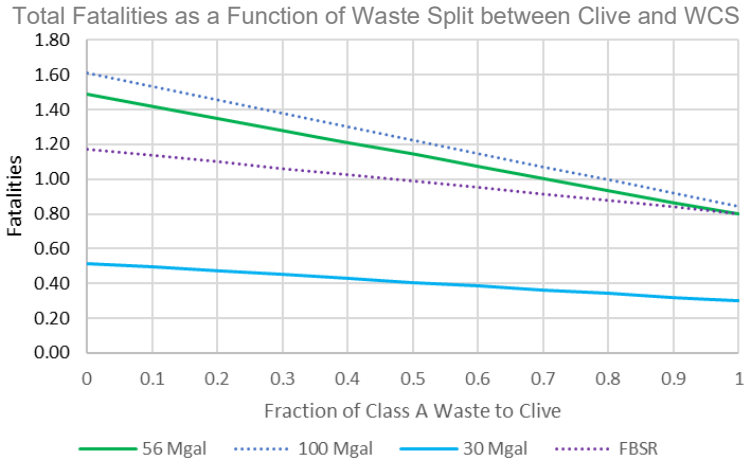


Figure H-52. Total Fatalities During Transportation Campaign

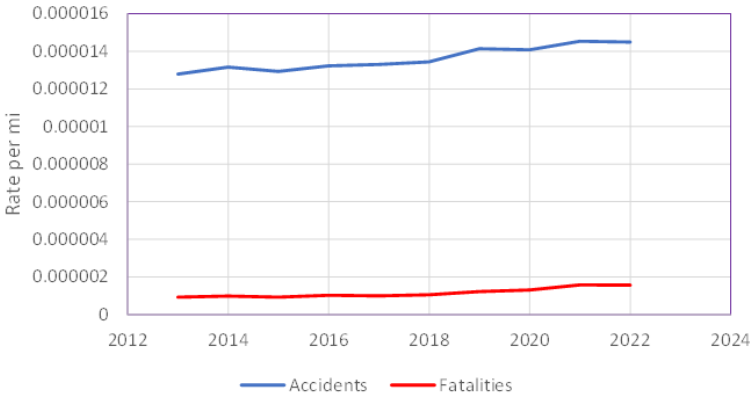


Figure H-53. Freight Train Accident and Fatality Rates

H.10 FEED VECTOR UNCERTAINTIES

Two feed vectors were used in this analysis – SP9 1B and Early Start. Both feed vectors describe the average monthly concentrations of 46 radionuclides over the time of waste generation. The radionuclide concentrations in the feed vectors were used to determine if the waste form (liquids, grout, and FBSR):

- Meet the LSA-II criteria for specific activity and dose rates
- Meet the waste acceptance criteria of the two off-site disposal sites (WCS and Clive).

Meeting LSA-II Criteria for Specific Activity

Radionuclide concentrations were used to calculate the specific activity (Ci/g) of liquid, grout, and FBSR waste forms over the period of generation (Section H.5). The specific activity was compared to the LSA-II criteria for liquids and solids. Both liquids and solids (grout and FBSR) meet the corresponding LSA-II specific activity limits during the entire period of operations. The liquids are at least one order of magnitude below the LSA-II limit for liquids with a few exceptions. Grout and FBSR are at least two orders of magnitude below the LSA-II limit for solids with a few exceptions. Consequently, the variations in the feed vector concentrations relative to the average monthly concentrations are not expected to result in exceeding the LSA-II limit. This is illustrated in the following example. As discussed in Section H.5, the major contributors to the mixture specific activity are ^{239}Pu and ^{241}Am.

Increasing concentrations of these radionuclides by 30% in every month of the feed vector results in a 5.4% (maximum) and 0.2% (average) increase in the difference between the LSA-II limit for liquids and the liquid specific activity (e.g., the liquid specific activity is significantly below the LSA-II limit for liquids); an even smaller impact would be seen for the grout and FBSR waste forms.

In addition, the International Atomic Energy Agency (IAEA) sponsored a working group with the goal of revising the A_1 and A_2 values to better align with radiological consequences (IAEA, 2022). IAEA plans to include these values in the next edition of Specific Safety Requirements (SSR)-6, *Regulations for the Safe Transport of Radioactive Material*, and these new values will then be incorporated into 49 CFR 173 and 10 CFR 71. The new A_2 value for ^{241}Am is two times higher than the original value, which means that the ^{241}Am radiological toxicity will be two times lower, and the LSA-II limit considered in this analysis will be somewhat higher (less stringent) for liquids, grout, and FBSR.

Meeting LSA-II Criteria for the External Dose Rates

The external dose rates meet the LSA-II external dose limits with the conservatively assumed maximum concentrations of radionuclides in the feed vectors, with the exception of 94th percentile of ^{137}Cs used with the Early Start feed vector.

The total activity of each radionuclide was calculated assuming an ISO tank volume of 5,000 gal. To meet nonfissile material exemptions, the transported liquid volumes will be 4,000 gal or less, as described in Section H.5. Consequently, the activities will be smaller.

If the activity of ^{137}Cs (a major contributor [~90%] to the external dose rate) in the ISO tank is determined to exceed 2.3 Ci, a smaller container can be used instead. Consequently, the variations in the feed vectors may affect the volume of the container, but will not preclude the transport of liquids.

Meeting Waste Acceptance Criteria

Figure H-20 to Figure H-24 (Section H.6) show the calculated sum of fractions for the long-lived and short-lived radionuclides for each month of grout production for the SP9 1B and Early Start feed vectors. The sum of fractions are significantly below the Class C limit. The Class C classification is driven by ^{241}Am and ^{239}Pu. To examine the sensitivity, the concentrations of these radionuclides were increased by 30% in both feed vectors during each month of waste generation. Table H-13 shows the results of the waste classification using the original feed vector concentrations (original case) and 30% higher ^{241}Am and ^{239}Pu concentrations (sensitivity case). The impact is very small – 1.2% to 1.4% increase in the combined Class B and Class C waste. Consequently, the variations in the feed vectors will not have a noticeable impact on waste acceptance.

Table H-13. Waste Classification Results for the Original and Sensitivity Cases

	Feed Vector SP9 1B		Early Start Feed Vector	
Waste Class	Original Case	Sensitivity Case	Original Case	Sensitivity Case
A	90.12%	88.91%	93.15%	91.72%
B	3.98%	2.64%	2.42%	1.94%
C	5.90%	8.45%	4.43%	6.34%

H.11 TECHNOLOGY READINESS LEVEL

The DOE Office of Packaging and Transportation (OPT) FY 2020 Highlights (DOE-OPT, 2021) provides evidence that the TRL is "high" for shipping immobilized supplemental LAW from the Hanford Site to WCS. The FY 2020 report is the most current report available. Accomplishments of DOE-OPT in FY 2020 included performing three Motor Carrier Evaluation Program evaluations on motor carriers involved in transporting DOE's hazardous materials and providing 92 Transportation Emergency Preparedness Program courses to train more than 1,433 first responders. "Hazardous materials" is a broad regulatory category that includes Class 7 radioactive materials.

In FY 2020, DOE completed more than 3,200 off-site hazardous material shipments over public roads and railroads totaling more than 6 million miles with no recordable packaging and transportation accidents. Approximately 242 shipments were by rail. Of approximately 1,500 shipments of radioactive material, 1,307 were waste shipments. These waste shipments included 325 LLW and 74 MLLW shipments; supporting evidence that the TRL for shipping immobilized LAW is high.

H.12 TECHNICAL RISKS

H.12.1 Transportation Risks for Transport from Hanford to Waste Control Specialists

The transport of goods by truck and railcar increases the amount of traffic, which increases the likelihood of traffic accidents and fatalities; in addition to increasing impacts to air quality, noise, and infrastructure. Statistically, these impacts are largely proportional to the number of miles traveled and independent of the cargo; transporting concrete blocks and transporting radioactive grout are the same. However, transporting radioactive materials does bring additional risks, including potential doses to workers and the public from routine transport and from transportation accidents.

NEPA requires Federal agencies to prepare an assessment of potential environmental impacts when providing reports and recommendations for Congressional funding. Actual implementation of a shipping program, such as outlined here, would potentially require the development of an EIS that would detail potential impacts to air quality, ecological resources, historic and cultural resources, noise, the public, and occupational health.

For the transport of radioactive materials, the EIS analysis of a large transportation program might specifically address:

- **Non-radiological impacts on local and national traffic** – The impacts of additional trains on local and national tracks and the associated impacts to air quality, noise, and infrastructure
- **Non-radiological impacts of transportation accidents** – Statistical number accidents and fatalities from a proposed transportation program
- **Radiological impacts of routine transportation** – Dose to a maximally exposed individual and the projected dose to the population along the route
- **Radiological impacts of transportation accidents** – Statistical doses from a hypothetical accident.

This study is not scoped to provide a detailed analysis of potential transportation impacts often provided in an EIS, but instead compares the risks from disposal of Hanford immobilized LAW to the risks calculated in the EIS for a similar campaign. In particular, the assessment of radiological impacts will need to be specific to the:

- Dose rate on the outside of the shipping package(s)
- Radiological content of the material(s) being shipped
- Form of the waste (solid, powder, liquid)

- Packaging
- Quantities of material(s) being shipped
- Mode (truck or rail)
- Possible accident scenarios for those waste forms
- Routing and population densities along the route.

DOE/EIS-0337F, *West Valley Demonstration Project Waste Management Environmental Impact Statement, Final Summary* (WVDP EIS), provides an example of an EIS for a major transportation program, including the shipping of LLW by rail to a disposal facility. The technical details of this EIS transportation analysis are presented in Appendix D of DOE/EIS-0337F.

H.12.2 Non-Radiological Transportation Risks from Hanford to Waste Control Specialists Scaled from the West Valley Demonstration Project

Many of the non-radiological transportation risks are proportional to the miles traveled, and some of the relative, non-radiological, risks can be assessed by scaling the analysis from an analogous EIS of the safety of rail transport of other radioactive wastes. The WVDP EIS includes a non-radiological transportation risk assessment that can be scaled to provide a sense of the relative risks of this transportation program.

The closest analogy from the WVDP EIS to the proposed program to transport immobilized LAW from Hanford to the commercial WCS disposal facility is based on the following in the WVDP EIS: Alternative A, rail transport of all LLW and MLLW from WVDP to Hanford (Hanford was once considered as a regional disposal facility for DOE-titled LLW). Specifically, under Alternative A, DOE would ship Class A, B, and C LLW (19,200 m^3 [25,113 yd^3]) and MLLW (221 m^3 [289 yd^3]) to the potential DOE disposal site in Washington State. Table H-14 summarizes key parameters for this Fiscal Year (FY) 2021 National Defense Authorization Act (NDAA21) Section 3125 study and those selected from the WVDP EIS.

Table H-14. Key Parameters for the NDAA21-3125 Study and Key Parameters from the West Valley Demonstration Project Environmental Impact Statement

Parameter	This NDAA21-3125 Study	WVDP EIS (DOE/EIS-0337F[a])
Mode	Rail	Rail
Transportation distance (one-way)	2,503 miles (Hanford to WCS) 1,213 miles (Hanford to Clive)	2,614 miles (WVDP to Hanford)
Type of wastes	MLLW	LLW and MLLW
Number of railcars, Grout SP9 1B Feed Vector	192 (1 year of grout at 16 railcars per month)	615 (all LLW+ MLLW, EIS Alternative A, Table G-3)
Number of railcars, FBSR SP9 1B Feed Vector	60 (1 year of FBSR at five railcars per month)	615 (all LLW+ MLLW, EIS Alternative A, Table G-3)
Number of railcars, Grout Early Start Feed Vector	360 (1 year of grout at 30 railcars per month)	615 (all LLW+ MLLW, EIS Alternative A, Table G-3)

[a] DOE/EIS-0337F, 2009, *West Valley Demonstration Project Waste Management Environmental Impact Statement, Final Summary*, U.S. Department of Energy, West Valley Area Office, West Valley, New York.

EIS = environmental impact statement.
FBSR = fluidized bed steam reforming.
LLW = low-level waste.
MLLW = mixed low-level waste.
NDAA21 = Fiscal Year 2021 National Defense Authorization Act.
WCS = Waste Control Specialists, LLC.
WVDP = West Valley Demonstration Project.

Although not an exact match, the two transportation programs are very similar, with both programs assessing the impacts of rail transport of LLW and MLLW over ~2,400 miles.

Transportation impacts for rail transport from the WVDP EIS (DOE/EIS-0337F) for Alternative A for all LLW and MLLW for the 2,614-mile trip are presented in Appendix D, Table D-16 of the WVDP EIS and summarized in Column 2 of Table H-15. Those Column 2 values are then scaled to provide relative transportation risks for this NDAA21-3125 study and presented in Columns 3 through 6 for the SP9 1B feed vector. For the Early Start feed vector, these impacts would be approximately doubled.

Because the WVDP EIS assesses impacts per railcar mile, two translation factors were applied to scale the EIS analysis to this NDAA21 transportation scope: a scaling for the differences in the transportation distances, and a scaling for the difference in the number of railcars. The translation factors are detailed as footnotes in Table H-15. The milage was doubled because a non-radiological accident may occur on the way to the disposal site (with the cargo) and on the way back (no cargo).

Table H-15. Relative Non-Radiological Risks, Scaled from the West Valley Demonstration Project Environmental Impact Study to this NDAA21-3125 Study

Impacts	Summed WVDP impacts, for rail, for Alternative A, for all LLW+MLLW	One average year of impacts, for Hanford Grout SP9 1B Feed Vector based on WVDP impacts	42 years of impacts, for Hanford Grout SP9 1B Feed Vector scaled from WVDP impacts	One average year of impacts, for Hanford FBSR SP9 1B Feed Vector based on WVDP impacts	42 years of impacts, for Hanford FBSR SP9 1B Feed Vector scaled from WVDP impacts
Traffic fatalities	0.10	0.060A	2.5B	0.019C	0.79B
Incident-free, pollution health effects	0.024	0.014A	0.60B	0.0045C	0.19B

Translation Factors:

A – WVDP multiplied by 0.31 (192/615 correction for number of railcars) and multiplied by 1.92 (5,006/2,614 correction for distance traveled).

C – Assumes 100% of Class A waste is disposed of at WCS; if all is disposed of at Clive the result would be ~1/2 of this value due to the shorter distance to Clive.

B – WVDP multiplied by 0.098 (60/615 correction for number of railcars) and multiplied by 1.92 (5,006/2,614 correction for distance travel).

FBSR = fluidized bed steam reforming.
LLW = low-level waste.
MLLW = mixed low-level waste.
WCS = Waste Control Specialists, LLC.
WVDP = West Valley Demonstration Project.

For this NDAA21-3125 study, the scaled statistical number of non-radiological rail traffic fatalities range from 0.79 to 2.5 for the summed 42 years of shipping treated LAW.

The WVDP EIS transportation analysis is based on rail accident rates compiled in 1999 (DOE/EIS-0337F, page D-11). The statistics for the freight trains for 2013–2022 are discussed in Section H.9. The average fatality rate is 1.17 E-06 per mile.

For a train from the Hanford Site to WCS, the roundtrip distance is 5,006 miles; assuming one train per month, a total of 60,000 train-miles per year, (statistically) would result in 0.072 fatalities per year and 2.95 fatalities over the full 42-year program. This value falls within the fatality range discussed in Section H.9. To put this impact (2.95 statistical fatalities in 42 years) in context, 42 years of baseline rail operations throughout the country would result in 22,558 statistical fatalities (i.e., 42 × 537 fatalities/year). Stated differently, 2.95 statistical fatalities represent an 0.02% increase in rail fatalities over the 42-year program.

H.13 PROGRAMMATIC RISKS

This NDAA21-3125 study completed a semi-quantitative assessment of risks, based on an elicitation of subject matter experts. This elicitation of risks identified:

- Initiating scenarios that could result in deviations from the design/operational intent
- The probability of the initiating scenario
- The unmitigated consequences
- The means of mitigating such events
- A probability of a successful mitigation
- The cost and schedule consequences of the mitigation.

This semi-quantitative assessment of risks identified and analyzed one programmatic risk for the off-site transportation program: Political opposition in a major city on the rail route following a rail accident causes DOE to temporarily stop the shipping program.

Based on experience, the probability of this occurring is low. However, the unmitigated consequences were judged to be very high costs and very high schedule impacts.

The mitigation strategy is to change the rail route or shift to shipping by truck. The probability of mitigation success is very high, and the mitigation consequences were assessed to be low cost and low schedule.

To avoid the risk of site-specific interruptions of such shipments, agreements with multiple immobilization and disposal sites are important and should be in effect for any such multi-year or multi-decade campaign.

Another programmatic risk is the potential unavailability of the two off-site disposal facilities. Currently, both facilities dispose of wastes received from the government, medical facilities, industry, and utilities. Liquid waste that is received is converted to solid waste before disposal. There has not been substantive stakeholder or political resistance to specific waste streams being disposed of at these sites, except the depleted uranium, which DOE proposed to dispose of at the Energy*Solutions* Clive site. Neither facility has ever declined a waste shipment. This is because both facilities have the ability to treat the waste in case it does not meet the waste acceptance criteria. In one case, DOE decided to recall a waste shipment sent for off-site disposal.

As discussed in Section H.6, 90% to 93% of grouted supplemental LAW (83% in the Early Start feed vector with off-site disposal until 2040) will be Class A waste. Class A waste can be disposed of either at Clive or WCS. The disposal volumes available at Clive and WCS can accommodate all Class A waste. The disposal volume at WCS can also accommodate all Class B and C waste. This capability provides substantial operational flexibility.

Transportation of radioactive materials has been accomplished routinely and safely in the U.S. and in many countries around the world. As discussed in Sections H.3.5 and H.3.6, DOE has extensive experience in shipping hazardous materials and in ensuring radioactive materials transportation safety. DOE works closely with state, tribal and local jurisdictions on transportation-related topics. Specifically, DOE has established a National Transportation Stakeholder Forum to engage at a national level with these stakeholders regarding DOE's shipments of radioactive materials and waste. The DOE Transportation and Emergency Preparedness Program conducts courses in emergency preparedness with state, tribal and local emergency responders to ensure that they have the necessary training and tools to respond to transportation accidents involving DOE radioactive material shipments.

In the unlikely event that one of the two off-site facilities becomes unavailable for receipt of supplemental LAW, the redundancy of two potential disposal sites with regard to ~90% of the waste is an important mitigation means. The mitigation measures include:

- Sampling and analyzing the waste first to ensure compatibility with the immobilization process
- Ensuring that any waste deemed incompatible with the immobilization process is directed to LAW vitrification in a "sample-and-send" approach
- Ensuring that both off-site permits/permit modifications (if any are needed) and agreements with off-site facilities are in place prior to initiation of any on-site grouting or any shipment of liquid supplemental LAW for off-site treatment/disposal. Such agreements could ideally provide for alternative off-site contingency disposition arrangements in the event that the contracted receiving facility cannot disposition the waste as expected.

There is a very small probability that both off-site disposal facilities would become permanently unavailable. If this occurs, it is highly probable that a large volume of waste would be already disposed of at one or both facilities. DOE would need to consider other options for the remainder of the waste, such as: (1) pursue identifying other locations that could accept this waste, (2) work with state regulators and stakeholders to determine a process that would allow DOE to dispose of grouted waste streams onsite, (3) pursue early construction and startup of on-site grouting and disposal for both alternatives Grout 4B and Grout 6, and/or (4) develop and implement removal of ^{99}Tc and ^{129}I, followed by on-site LAW grout disposal (Grout 1C).

H.14 REFERENCES

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49 CFR 171.7, "Reference Material" *Code of Federal Regulations*, as amended.

49 CFR 172, "Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, Training Requirements, and Security Plans," *Code of Federal Regulations*, as amended.

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Appendix I. Supplemental Regulatory Background and Information

I.1 INTRODUCTION

Section 3125 of NDAA21 calls for continued analysis of approaches for supplemental treatment of LAW as a follow-on to the analysis required by Section 3134 of NDAA17. Although the focus of the FFRDC follow-on report is technical, NDAA17 Section 3134 requested analysis of "compliance with applicable technical standards" with respect to the approaches for supplemental treatment of LAW evaluated by the FFRDC. Key aspects of these laws and regulations that bear on alternatives selection are discussed in Section 2.0 of this report and in the Washington State Department of Ecology's (Ecology) response to questions from the FFRDC team (Volume II, Appendix J). Additional background and supplementary information are provided in this appendix with respect to:

- *Solid Waste Disposal Act* (commonly referred to as the *Resource Conservation and Recovery Act of 1976* [RCRA])
- DOE O 435.1, *Radioactive Waste Management*, which implements the *Atomic Energy Act of 1954*
- *Federal Water Pollution Control Act* (commonly referred to as the *Clean Water Act of 1972* [CWA])
- *Clean Air Act of 1972* (CAA)
- *National Environmental Policy Act of 1969* (NEPA)
- *Hanford Federal Facility Agreement and Consent Order – Tri-Party Agreement* (TPA) (Ecology et al., 1989)
- *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA).

The FFRDC team continued the analysis previously begun, analyzing the regulatory aspects of Hanford supplemental LAW treatment and disposal alternatives. The team also considered additional information that became available following issuance of the previous analysis.

Based on this assessment, the FFRDC team concluded that requirements from RCRA, including sub-elements of the Land Disposal Restrictions (LDR) and RCRA Treatment, Storage, and Disposal Unit Permitting, may present different considerations for the different alternatives. The team concluded that requirements from the DOE O 435.1, CWA, CAA, NEPA, TPA, and CERCLA likely would not present different considerations for the different alternatives. The regulatory aspects are discussed in more detail in the subsections that follow. Information regarding transportation is provided in Volume II, Appendix H.

I.2 RESOURCE CONSERVATION AND RECOVERY ACT

The *Solid Waste Disposal Act* was established in 1965 and recognized the environmental consequences associated with waste disposal practices. In 1976, Congress passed RCRA, which amended the Solid Waste Disposal Act. RCRA set national goals for protecting human health and the environment from potential waste disposal hazards, conserving natural resources, and reducing generated waste. One of the programs under RCRA is the hazardous waste management program, identified as Subtitle C, which is codified in Title 40, Code of Federal Regulations, Parts 260 through 273 (40 CFR 260–273). Under Subtitle C, U.S. Environmental Protection Agency (EPA) has the authority to regulate hazardous waste management activities—including treatment, storage, and disposal--from "cradle [waste generation] to grave [disposal]". RCRA allows EPA to "authorize" states to implement most elements of the Subtitle C regulatory program, so long as pertinent state program requirements are at least as stringent as the federal requirements, while retaining EPA's right to enforce RCRA requirements where necessary. Where specific RCRA program elements are authorized by EPA, state RCRA requirements operate in lieu of the federal requirements.

EPA has authorized Washington, Utah, and Texas to implement various hazardous waste management program elements relevant to the issues addressed in the FFRDC report, including permitting requirements for treatment, storage and disposal facilities, and Land Disposal Restrictions (LDR) for hazardous wastes and constituents. The LDR requirements are discussed in Section 2 of the Report. EPA-authorized state RCRA permitting requirements for Washington, Utah and Texas are discussed below.

In Washington State, Ecology has been authorized by EPA to administer hazardous waste regulations, including permitting (51 FR 3782, "Washington; Final Authorization of State Hazardous Waste Management Program"). Provisions of the Washington State Hazardous Waste Management Act (RCW 70.105, "Hazardous Waste Management") are promulgated in *Washington Administrative Code* (WAC) 173-303, "Dangerous Waste Regulations," and can include additional state requirements.

In Utah, the Utah Department of Environmental Quality has been authorized by EPA to administer hazardous waste regulations, including permitting (49 FR 39683, "Utah Decision on Final Authorization of State Hazardous Waste Management Program"). Provisions of Title 19, Chapter 6, Part 1, "Solid and Hazardous Waste Act," are promulgated in the *Utah Administrative Code*, Title R315, "Waste Management and Radiation Control, Waste Management" (Utah R315) and may include more stringent and/or different state requirements.

In Texas, the Texas Commission on Environmental Quality (previously known as the Texas Natural Resource Conservation Commission) has been authorized by EPA to administer hazardous waste regulations, including permitting (49 FR 48300, "Texas; Decision on Final Authorization of State Hazardous Waste Management Program"). Provisions of the *Solid Waste Disposal Act* (Texas Health and Safety Code 361.001 to 361.912 [Texas HS-361]) are promulgated in Title 30, *Texas Administrative Code* (TAC), Chapter 335 (30 TAC 335), "Industrial Solid Waste and Municipal Hazardous Waste" and may include more stringent and/or different state requirements.

Resource Conservation and Recovery Act Permitting Background

Facilities that treat, store, or dispose of hazardous waste are required to obtain a RCRA permit, which is a legally binding document outlining how the facility is managed. Permits include descriptions of:

- Treatment, storage and/or disposal designs, processes, and capacities
- Waste acceptance methods
- Groundwater monitoring (for land-based units, such as landfills and surface impoundments)
- Security measures
- Precautions to prevent hazards and emergency preparedness procedures
- Dangerous waste training plan
- Plan for closure of the unit
- Facility inspections.

To incorporate a new facility into an existing RCRA permit or significantly modify an existing facility, a permit modification request is submitted by the Permittee to the state in which the facility resides. Permit modifications must include applicable information associated with the change requested.

Following submittal of the permit modification request to the state regulatory agency, a notice is issued informing the public and local/state governments that a review period is forthcoming. The permit modification request for a new facility or significant modification is then made available for public review and a public meeting is held, providing the public an opportunity to obtain additional information about the permit modification request.

Following completion of the initial public comment period, the state agency assesses the permit modification request and prepares responses to public comments. At this time, the state agency can make a decision on less significant permit modification requests.

For more significant permit modification requests that have successfully completed the initial public comment process, the state agency will develop a draft permit, which will be issued for an additional public comment period. The state agency will issue a notice informing the public of an upcoming public comment period and a factsheet summarizing the change(s). Once the public comment period begins, a public hearing may be held. All public comments are responded to and made available. Upon resolution of public comments, the state regulatory agency can issue the permit.

The treatment and disposal component of any alternative that requires significant modification to existing facilities or requires construction of a new facility would necessitate completion of the permit modification process before commencement of construction (EPA 530-R-16-013, *Resource Conservation and Recovery Act Public Participation Manual*).

The treatment and/or disposal facilities described in this FFRDC report that operate under a RCRA permit are Hanford, Energy*Solutions* Disposal Facility (Clive, Utah), Waste Control Specialist, LLC (WCS) Federal Waste Disposal Facility (Andrews, Texas), and PermaFix in Washington and Tennessee.

The Hanford Site manages both hazardous and radioactive mixed waste. The permitting framework for Hanford was established in the TPA, which recognizes Hanford as a single RCRA facility (EPA RCRA ID WA7890008967) consisting of numerous treatment, storage, and disposal units (TSD), including the Integrated Disposal Facility (IDF) and the Waste Treatment and Immobilization Plant (WTP) (Ecology, 2022a).

Energy*Solutions* manages mixed waste and has a single EPA ID number (UTD 982598898) (BWF WAC, 2015). Mixed waste management occurs in a disposal cell, treatment building, storage building, and operations building (Downs, 2003).

WCS manage both hazardous and mixed waste under two EPA ID numbers. Hazardous waste permit 50397 (EPA ID TXR000075788) authorizes storage and disposal of mixed and industrial radioactive waste from federal sources. Hazardous waste permit 50358 (EPA ID TXD988088464) authorizes storage, treatment, and disposal of hazardous or Texas exempt waste only (WCS, 2022a).

PermaFix Northwest (PermaFix, 2022b), located in Washington State, manages mixed waste and has a single EPA ID number (WAR000010355). Treatment and storage of mixed waste occurs within a single containment building. PermaFix Diversified Scientific Services (DSSI), located in Tennessee, is authorized for storage and treatment of mixed waste under a single EPA ID number (TND982109142 [EPA, 2022]). Treatment includes thermal and liquid waste treatment capabilities (PermaFix, 2022a).

An additional challenge related to disposal is the long-term performance of the LAW supplemental treatment waste form. With regard to on-site disposal, mitigation measures may be required if modeling projects that future groundwater concentrations may exceed 75% of the maximum contaminant limit (IDF Permit Condition III.11.I.5.a.ii [Ecology, 2021]). The IDF Performance Assessment evaluates a 1,000-year compliance period as well as a 10,000-year post-compliance, sensitivity analysis period (RPP-RPT-59958). This issue is evaluated under the long-term performance criterion in Volume II, Appendix D. Additional information regarding long-term performance can be found in the NDAA17 study (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*).

Table I-1 summarizes RCRA aspects of the alternatives.

Table I-1. Resource Conservation and Recovery Act Aspects

Alternative	RCRA Aspects
Vitrification	• Vitrification has been approved by WA Ecology for treatment of tank LAW at Hanford. Vitrification destroys most organic chemicals and nitrate/nitrites but does generate a significant volume of secondary waste that has been estimated to include significant amounts of hazardous constituents that as secondary waste are not subject to LDR requirements. Liquid secondary waste is intended to be treated as wastewater and residuals grouted. For supplemental LAW vitrification, alternatives would require RCRA permitting actions to increase capacity at the existing WTP or to add additional facilities to the Hanford Facility RCRA Permit. • In disposing of the vitrified waste form, mitigation measures may be required if modeling projects that future groundwater concentrations exceed 75% of the maximum contaminant limit. The vitrified waste forms would be disposed of onsite, and additional permitting actions for disposal are not anticipated.
Fluidized Bed Steam Reforming	For FBSR, alternatives would require RCRA permitting actions to add one or more steam reforming facilities to the Hanford RCRA permit. The steam reforming waste forms and secondary waste if to be disposed of onsite, would require additional RCRA permitting actions. Disposal of a steam reformed waste form at an off-site facility is not expected to require additional RCRA permitting because the locations selected already have permitting in place to receive solidified waste forms.
Grout	• On-site grout treatment and disposal alternatives would require RCRA permitting actions to add one or more grout facilities to the Hanford RCRA permit. Disposal of grouted LAW onsite would require a modification to the IDF permit for the grouted waste form and any associated secondary waste not already addressed in an in-process permit modification. Grouted liquid secondary waste from WTP is in the process of being permitted for disposal at IDF. • One alternative considered by the FFRDC team included a monolith waste form rather than smaller, containerized waste forms for LAW disposed at Hanford. Disposal of a monolith waste form would require permitting of a new on-site disposal facility. • New Hanford facilities may also require lag storage for grouted waste forms prior to transfer to the disposal facility. For off-site treatment of waste, all proposed facilities have existing RCRA permits for grouting low-level waste, but additional RCRA permitting may be required for potential expansion to include new waste streams or increased quantities. • For on-site disposal of the grouted waste form, mitigation measures may be required if modeling projects that future groundwater concentrations exceed 75% of the maximum contaminant limit (IDF Permit Condition III.11.I.5.a.ii [Ecology, 2021]). The IDF Performance Assessment evaluates a 1,000-year compliance period as well as a 10,000-year post-compliance sensitivity analysis period (RPP-RPT-5598). • Disposal of a grouted waste form at an off-site facility is not expected to require additional RCRA permitting because the locations selected already have permitting in place to receive grouted waste forms.

Ecology = Washington State Department of Ecology.
FBSR = fluidized bed steam reforming.
FFRDC = Federally Funded Research and Development Center.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
RCRA = Resource Conservation and Recovery Act.
WTP = Waste Treatment and Immobilization Plant.

I.3 DOE O 435.1, RADIOACTIVE WASTE MANAGEMENT

The portion of LAW at Hanford that is intended for supplemental treatment, and addressed in this assessment, is managed through DOE's radioactive waste management activities as prescribed under various DOE Orders, including DOE O 435.1. DOE O 435.1 was promulgated under the *Atomic Energy Act of 1954*. DOE is the responsible party for the safe management and final disposal of all radioactive wastes arising from its operations. The objective of the activities required under this Order is to ensure that the waste is managed in a manner that is protective of worker and public health and safety, and the environment (SRNL-RP-2018-00687).

In 1997, DOE and Nuclear Regulatory Commission (NRC) provisionally agreed that the majority of waste from Hanford tanks is not high-level waste (HLW) and is low-level waste (LLW) that is not subject to NRC's licensing authority. DOE has been using the Waste Incidental to Reprocessing (WIR) criteria in DOE M 435.1-1, *Radioactive Waste Management Manual*, which implements DOE O 435.1, to make determinations as to whether Hanford tank waste can be disposed of as mixed low-level waste (MLLW). Incidental waste is managed under DOE's regulatory authority in accordance with the requirements for LLW, as appropriate. If shown to meet the criteria outlined in DOE M 435.1-1, the waste stream can be disposed of in a near-surface facility (SRNL-RP-2018-00687).[1]

As defined in DOE M 435.1-1, classification of waste incidental to reprocessing is achieved by DOE documenting that the waste meets the following criteria:

1. Has been processed, or will be processed, to remove key radionuclides to the maximum extent that is technically and economically practical
2. Will be managed to meet the safety requirements comparable to the performance objectives set out in 10 CFR 61, Subpart C, "Performance Objectives" (performance objectives are specific to the disposal location)
3. Are to be managed pursuant to DOE's authority under the *Atomic Energy Act of 1954*, and in accordance with the provisions included in DOE M 435.1-1, Chapter IV, provided the waste will be incorporated in a solid physical form at a concentration that does not exceed the applicable concentration limits for Class C LLW as set out in 10 CFR 61.55, "Waste Classification;" or will meet alternative requirements for waste classification and characterization as DOE may authorize.

A WIR Evaluation, drafted by DOE, documents that treatment of waste to remove key radionuclides, safety requirements comparable to the performance objectives defined in 10 CFR 61, Subpart C (e.g., meet performance assessment [PA] requirements), and transformation of waste into a solid physical form that meets NRC Class C LLW or lower NRC classifications.

The draft WIR Evaluation may be provided to NRC for consultation and made available for public review, including by states, Tribal Nations, and other stakeholders. After responding to any requests for additional information from the NRC and comments from the public, DOE prepares a final WIR Evaluation. Based on the final WIR Evaluation, DOE may determine, in a WIR Determination, whether the waste is incidental to reprocessing, is non-HLW, and may be managed as LLW (DOE M 435.1-1).

The draft Vitrified LAW WIR (DOE-ORP-2020-01) was submitted for public comment and NRC review on May 26, 2020. The draft WIR provides a technical basis for determining that the vitrified LAW to be disposed of onsite at IDF is waste that is incidental to reprocessing and may be managed as MLLW (85 FR 31479). A final WIR Evaluation had not been issued as of the publication date of this report.

[1] DOE M 435.1-1 also includes the Department's HLW interpretation (84 FR 26835) as an approach for determining when a reprocessing waste is non-HLW. Specifically, Chapter II of the Manual sets forth the HLW interpretation and provides a basis for its use by DOE.

Two separate WIR Evaluations were drafted for the TBI to demonstrate that the separated, pretreated, and solidified tank waste meets the criteria in DOE M 435.1-1 and is waste incidental to reprocessing. Under the proposed TBI demonstrations, the pretreated waste will be grouted and the solidified waste will be disposed as MLLW at an off-site facility (DOE, 2021 and DOE-EM, 2018a). The first WIR addressing grouting of 3 gal of LAW was approved, and this waste was subsequently treated and disposed in 2017 (DOE-EM, 2018b). The second WIR Evaluation, addressing approximately 2,000 gal of LAW, was provided for NRC and public review in November 2021 but a WIR Determination has not been made with respect to this batch of LAW.

Table I-2 summarizes WIR aspects of the alternatives.

Table I-2. Waste Incidental to Reprocessing Aspects[a]

Alternative	WIR Aspects
Vitrification	The VLAW WIR has completed NRC and public review, and responses to requests for additional information are in process. Vitrification treatment alternatives are consistent with the in-process VLAW WIR.
Fluidized Bed Steam Reforming	• Choosing an FBSR option as a treatment alternative may entail a separate WIR evaluation for on-site disposal. • Although FBSR is related to the process that has been constructed and currently under testing at INL in anticipation of treatment of sodium-bearing tank waste, an equivalent process has not been performed in the DOE complex. A WIR consultation for INL carbonate-based remote-handled transuranic waste occurred, and an approved WIR will likely be required. The steam reforming aluminosilicate mineral waste form proposed for Hanford is different than the carbonate waste form at INL.
Grout	• Choosing a grout option as a treatment alternative will require a separate WIR Evaluation for disposal. The completed TBI Demonstration WIR provides evidence that a WIR for grouting tank waste can be obtained for off-site disposal of Hanford tank waste. However, the TBI WIR involves off-site disposal. In addition, the SRS received a Section 3116 Determination (equivalent to the WIR process) to grout the SRS tank waste.[b] • In the requests for additional information on the VLAW WIR, NRC requested information on the basis of DOE's assertion that "key radionuclides would be removed to the maximum extent practical considering that most of the risk significant radionuclides ^{14}C, ^{3}H, ^{99}Tc, and ^{129}I may end up in other waste streams."[c]

[a] Evaluation of WIR aspects as they relate to Hanford tank waste treatment and disposal are based on DOE's current approach to use a WIR determination.

[b] NRC, 2005, *NDAA Section 3116 Waste Incidental to Reprocessing (WIR) at the Savannah River Site (SRS) in South Carolina – Saltstone Disposal Facility (SDF)*, https://www.nrc.gov/waste/incidental-waste/wir-process/wir-locations/saltstone.html, U.S. Nuclear Regulatory Commission, Washington, D.C.

[c] NRC, 2021, "Hanford Vitrified Low Activity Waste (VLAW) Draft WIR Evaluation, 9/9/2021 DOE-NRC Teleconference Summary," https://www.nrc.gov/docs/ML2132/ML21322A057.pdf, U.S. Nuclear Regulatory Commission, Washington, D.C.

DOE = U.S. Department of Energy.
FBSR = fluidized bed steam reforming.
INL = Idaho National Laboratory.
NRC = U.S. Nuclear Regulatory Commission.
SRS = Savannah River Site.
TBI = Test Bed Initiative.
VLAW = vitrified low-activity waste.
WIR = Waste Incidental to Reprocessing.

I.4 CLEAN WATER ACT

The CWA is intended to restore and maintain the chemical, physical, and biological integrity of the nation's waters. The CWA states that the policy is to recognize, preserve, and protect the responsibilities and rights of states to prevent, reduce, and eliminate pollution, and to plan the development and use of land and water resources (33 USC 1251, "Congressional Declaration of Goals and Policy"). State authorized programs applicable to this FFRDC report are in Washington State, Utah, and Texas.

Hanford does not have any current or planned discharges to the Columbia River (or other surface water) regulated under the CWA. Ecology establishes water quality standards for discharges to ground and surface waters of the state of Washington (WAC 173-216, "State Waste Discharge Permit Program"). Hanford operates under State Waste Discharge Permits (Ecology, 2022b):

- ST-4500 for the 200 Area Effluent Treatment Facility (ETF)
- ST-4502 for the 200 Area Treated Effluent Disposal Facility (TEDF)
- ST-4511 for miscellaneous streams
- ST-0045514 for the 200 West Area Evaporative Sewage Lagoon.

Waste streams resulting from the proposed on-site treatment alternatives that would be disposed of on the Hanford Site in accordance with the state water discharge program are bounded by existing Hanford waste streams originating from the WTP and 242-A Evaporator and processed through the ETF prior to disposal. No additional water discharge permitting is anticipated for the Hanford Site to support supplemental LAW activities.

The Utah Department of Environmental Quality is responsible for water quality standards for Utah (Utah Code 19-5). Energy*Solutions* operates under Ground Water Quality Discharge Permit number UGW450005 (UDEQ, 2014).

The Texas Commission on Environmental Quality is responsible for water quality standards for Texas (Texas Water Code, Chapter 26 [TWC WA.26]). WCS operates under Texas Pollutant Discharge Elimination System (TPDES) Permit Number WQ0004857000 (EPA ID TX0131644).

The FFRDC team assumed that wastewater streams resulting from off-site treatment would be disposed of in accordance with existing CWA permits (if available) or managed under RCRA. Additional off-site CWA permitting is not anticipated.

Table I-3 summarizes CWA aspects of the alternatives.

Table I-3. Clean Water Act Aspects

Alternative	Clean Water Act Aspects
Vitrification	Vitrification alternatives would not result in CWA waste streams that exceed current permit limits.
Fluidized Bed Steam Reforming	FBSR alternatives would not result in CWA waste streams that exceed current permit limits.
Grout	On-site grout alternatives would not result in CWA waste streams that exceed current permit limits. Additional off-site CWA permitting is not anticipated.

CWA = Clean Water Act. FBSR = fluidized bed steam reforming.

I.5 CLEAN AIR ACT

The CAA is a comprehensive Federal law intended to protect nationwide public health and welfare through the establishment of national air quality standards. The CAA was designed to minimize pollution from a range of sources, which can include both treatment and disposal facilities. States must adopt and enforce plans to meet air quality standards (42 USC 85 [7401]). State authorized programs applicable to alternatives discussed in this report are in Washington State, Utah, Tennessee, and Texas.

Air emissions at the Hanford Site are regulated under the Hanford Site Air Operating Permit (state license No. FF-01) and managed by Ecology for toxic and criteria pollutants (WAC 173-400, "General Regulations for Air Pollution Sources," and WAC 173-460, "Controls for New Sources of Toxic Air Pollutants"), and the Washington State Department of Health (WDOH) for radioactive pollutants (WAC 246-247, "Radiation Protection—Air Emissions"). Prior to any construction or modification activity that would result in an increase in emissions, a Notice of Construction application needs to be submitted to both Ecology and WDOH for review and approval.

Air permitting is based on emissions, not the treatment process, but does require demonstration of best available control technology to abate emissions. On the Hanford Site, Ecology has expressed concerns with tank vapors and has emphasized that additional toxic abatement measures will be required for new facilities constructed to treat tank waste. Additional air permitting may also be required for on-site disposal of waste.

Air emissions at the Energy*Solutions* Clive Disposal Facility are regulated under permit number DAQE-AN107170021-19 and managed by the Utah Department of Environmental Quality.

Air emissions are regulated at WCS under two permits:

- Air Quality Permit number 72653 (Wilson, 2016) regulates toxic air emissions, in accordance with 30 TAC 116.314.
- Compliance with Radioactive Material License No. R04100 (WCS, 2022b) is required for potential air emissions of radionuclides.

Both permits are managed by the Texas Commission on Environmental Quality. Prior to any construction or modification activity that would result in a change in emissions, an amendment to the permits must be requested.

Table I-4 summarizes CAA aspects of the alternatives.

Table I-4. Clean Air Act Aspects

Alternative	Clean Air Act Aspects
Vitrification	Although a major stack is currently permitted for WTP vitrification, additional permitting would be required for a change in throughput at WTP due to a change in emissions, or construction of an additional facility. CAA permits are in effect for disposal of vitrified LAW at IDF.
Fluidized Bed Steam Reforming	• FBSR would require permitting an offgas system with an associated stack. A steam reforming plant would be new to the Hanford Site and would require similar permitting to vitrification. • Disposal of an FBSR waste form at IDF may require additional air permitting similar to grouted waste forms. Disposal of an FBSR waste form at an off-site facility is not expected to require additional air permitting because the locations selected already have air permitting in place that is not specific to a waste form.
Grout	• An on-site grout facility, including an evaporator, will require air permitting for an additional source. Emissions would be bounded by similar evaporator units previously permitted at the Hanford Site (e.g., 242-A Evaporator and ETF). New off-site grout treatment facilities would also require air permitting. • Disposal of a grouted waste form at IDF may require additional air permitting. Disposal of a grouted waste form at an off-site facility is not expected to require additional air permitting because the locations selected already have permitting in place to receive grouted waste forms.

CAA = Clean Air Act.
ETF = Effluent Treatment Facility.
FBSR = fluidized bed steam reforming.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
WTP = Waste Treatment and Immobilization Plant.

I.6 NATIONAL ENVIRONMENTAL POLICY ACT

NEPA requires federal agencies to incorporate environmental considerations in decision-making prior to taking action, including making decisions on permit applications, adopting land management actions, and constructing facilities. Under NEPA, agencies also evaluate the related social and economic effects of proposed actions (40 CFR 1500, "Purpose and Policy").

An environmental review documenting the environmental considerations is required. Documentation can involve three different levels of analysis (40 CFR 1500):

- **Categorical exclusion determination**: An action may be categorically excluded from detailed analysis when there are no significant effects on the human environment.
- **Environmental assessment**: An environmental assessment determines whether or not a federal action has the potential to cause significant environmental effects.
- **Environmental impact statement (EIS)**: An EIS is prepared for a proposed major federal action that has been determined to significantly affect the quality of the human environment.

DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC&WM EIS), implements the NEPA requirement for environmental consideration of tank waste management through the WTP. In the EIS, DOE proposed supplemental treatment for LAW to meet TPA requirements. The TC&WM EIS evaluated thermal treatment, including vitrification and steam reforming, as well as nonthermal treatment (e.g., Cast Stone). The Record of Decision stated: "DOE does not have a preferred alternative regarding supplemental treatment for LAW; DOE believes it is beneficial to study further the potential cost, safety, and environmental performance of supplemental treatment technologies." Consequently, additional NEPA review is anticipated prior to selection of a preferred alternative.

Table I-5 summarizes NEPA aspects of the alternatives.

Table I-5. National Environmental Policy Act Aspects

Alternative	NEPA Aspects
Vitrification	Vitrification is addressed by DOE/EIS-0391;[a] however, a preferred alternative for supplemental LAW was not selected, and consequently additional NEPA review is anticipated.
Fluidized Bed Steam Reforming	FBSR is addressed by DOE/EIS-0391;[a] however, a preferred alternative for supplemental LAW was not selected, and consequently additional NEPA review is anticipated.
Grout	Grouting is addressed by DOE/EIS-0391;[a] however, a preferred alternative for supplemental LAW was not selected, and consequently additional NEPA review is anticipated.

[a] DOE/EIS-0391, 2012, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington*, U.S. Department of Energy, Office of River Protection, Richland, Washington.
FBSR = fluidized bed steam reforming. NEPA = National Environmental Policy Act.
LAW = low-activity waste.

I.7 TRI-PARTY AGREEMENT

Information on the Tri-Party Agreement is provided in Volume I, Section 2.0.

I.8 COMPREHENSIVE ENVIRONMENTAL RESPONSE, COMPENSATION AND LIABILITY ACT

CERCLA was enacted by Congress in December 1980 and established requirements concerning closed and abandoned waste sites, liability for responsible parties, and a fund for cleanup (42 USC 103 [9601]). Tank waste in the SSTs and DSTs is managed under RCRA, and consequently CERCLA is not relevant to tank waste treatment and disposal operations.

I.9 REFERENCES

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33 USC 1251, "Congressional Declaration of Goals and Policy," *United States Code*, https://www.law.cornell.edu/uscode/text/33/1251, as amended.

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85 FR 31479, 2020, "Notice of Availability of Draft Waste Incidental to Reprocessing Evaluation for Vitrified Low Activity Waste for Onsite Disposal at the Hanford Site, Washington," *Federal Register*, Issue 101 (May 26).

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Appendix J. Washington State Department of Ecology Responses to FFRDC Team Questions

The Federally Funded Research and Development Center (FFRDC) team developed a set of questions addressed to the Washington State Department of Ecology to better understand the positions and bases for positions related to regulatory approvals and permitting related to supplemental treatment of low-activity waste (LAW). The responses are attached as they were received.[1]

[1] Bowen, D., 2022, "RE: Questions Related to Hanford SLAW," (email to W. Bates, February 9, Savannah River National Laboratory), Washington State Department of Ecology, Richland, Washington.

**Washington State Department of Ecology Responses to
FFRDC Questions for Ecology regarding Regulatory Issues on the Report on
Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation**

Introduction

Thank you for the opportunity to respond to questions related to the FFRDC's report on Supplemental Treatment of Low-Activity Waste (LAW) at the Hanford Nuclear Reservation. The Washington State Department of Ecology (Ecology) attempted to address as many of the FFRDC's questions as possible and/or appropriate.

While it is not possible for Ecology to answer all the questions you posed individually, we would like to provide the information we think may be helpful to development of your report. To those ends, we offer the following general comments as preface.

To begin, many of the FFRDC's questions relate to technically and legally complex subjects better suited for discussion within the context of a Supplemental Treatment negotiation and/or a Supplemental Treatment "down select" process. Ecology believes that that such conversations should occur directly between Ecology, as the regulatory agency, and the United States Department of Energy (DOE), as the regulated entity. Indeed, we note that those discussions are already set to occur after DOE's ongoing High Level Waste Analysis of Alternatives process is complete. As a result, Ecology's responses to the FFRDC's questions should not be construed as either comprehensive or binding for purposes of those future negotiations.

Tank waste treatment at Hanford is a top priority for State of Washington. As such, Ecology believes that prioritization must be given to the commissioning and operation of the Direct Feed Low Activity Waste (DFLAW) vitrification system and the resumption of construction and completion of the High Level Vitrification Facility. This should be followed by the completion of a Hanford tank waste pretreatment system to wash the chemicals from high-level sludges and manage liquids.

Ecology acknowledges that additional treatment capacity for Supplemental Low Activity Waste (SLAW) will be required. However, that capacity will not be needed for *decades* because the activity that will produce that waste (sludge washing) will not occur until a pretreatment facility is constructed and operational, which could be in the 2040s to 2050s based on discussions with USDOE. As a result, significant time remains to make a Supplemental LAW treatment decision. It would be imprudent to rush to judgment at this time because critical new facts and knowledge about the treatment system and its capacity will be learned in the coming decades.

Recently, there have been discussions at Hanford regarding adding early additional Low Activity Waste (LAW) treatment capacity to run in parallel with DLFAW. In general, the conversation has focused on DOE's Test Bed Initiative (TBI) or other forms of "Alternative Treatment."

The goal of these efforts is to retrieve tank waste liquids in the West Area tank farms and pretreat those wastes in a new tank side cesium removal (TSCR) system. The waste would then be shipped to an offsite grout facility for stabilization, and the grouted waste would be sent to an out-of-state disposal site (such as the Waste Control Specialists facility in Texas). The advantage of the out-of-state disposal site is it's unique geology that can protect human health and the environment from the release of long-lived mobile constituents.

From Ecology's perspective, there is a key and fundamental difference between SLAW treatment and Alternative Treatment (or TBI). SLAW treatment occurs significantly in the future, after sludge washing of high-level waste (HLW) occurs in the yet-to-be-completed pretreatment facility. The assumption for SLAW is that it would be treated and disposed *at Hanford*. In contrast, Alternative Treatment/TBI involves the disposition of LAW that could occur in the near future, with liquid waste pretreated for cesium removal and then grouted for disposal *offsite*. Because these are separate issues, Ecology has differing concerns for each.

For Alternative Treatment/TBI, Ecology supports DOE proceeding with the next phase of TBI and believes that exploring the viability of—and resolving roadblocks for—this approach is beneficial to DOE and Ecology's shared mission to safely treat and dispose of Hanford's tank waste. Moreover, Ecology supports adding to the existing treatment capacity for Hanford's waste by utilizing offsite disposal. Indeed, Ecology remains ready to issue the Research, Development, and Demonstration permit for TBI that we prepared for public comment in 2019.

However, in pursuing TBI, all parties should acknowledge and be aware of significant constraints. TBI must not undermine or divert resources from the completion and future success of DFLAW or the HLW Vitrification facility. In addition, once tank waste destined for offsite disposal is retrieved, it must be shipped for treatment and ultimate offsite disposal in a timely manner.

Most importantly, enforceable agreements need to be made with the disposal facility and the regulatory agency for the state in which the facility is located, guaranteeing the acceptability of grouted tank waste for disposal. Such agreements need to be in place before grouting occurs, in order to protect against the risk of burdening Washington with orphaned waste in a form that is not protective of the Hanford aquifer and the Columbia River.

For Supplemental Treatment, Ecology's position is that immobilization must be accomplished by vitrification. This is what the Tri-Party Agreement (TPA) requires, and it remains the only option outlined in DOE's Tank Closure and Waste Management Environmental Impact Statement (TC & WM EIS) that would be protective of the groundwater at Hanford given the constraints at the site.

For any tank waste to be disposed of on site at Hanford, Ecology maintains that it must be incorporated into a waste form that has been demonstrated to be "as good as glass," especially with respect to long-lived, mobile constituents. The Resource Conservation and Recovery Act (RCRA) also requires that metals associated with HLW be treated to the Land Disposal Restrictions (LDR) treatment standard of HLVIT.

In the past, Ecology has considered other treatment options, such as bulk vitrification, for SLAW destined for disposal on the Hanford site, and Ecology has participated in "down select" efforts to identify alternatives for SLAW treatment by identifying values and criteria for acceptable options. When it is time for Ecology and DOE to consider and decide upon treatment options for SLAW, we will follow a similar pattern. However, DOE must be a collaborating partner in those discussions.

Finally, and informed by Ecology's experience of reviewing related FFRDC documents, Ecology urges the FFRDC to consider the following items in future documents considering SLAW:

- Vitrification is the baseline. Supplemental Treatment options must protect human health and the environment to *at least* that same level, for the same timeframe. In other words, the waste form must be "as good as glass" in order to be disposed at Hanford.
- Supplemental Treatment options will not be acceptable unless they are demonstrated to protect both the groundwater at the Hanford site and the Columbia River against contamination above current accepted drinking water standards; they must also satisfy the "inadvertent intruder" analyses in 10 C.F.R. Part 61.42.
- For any tank waste that is not treated to meet the HLVIT standard as defined under RCRA, DOE will need to obtain a treatability variance from Ecology in order to legally dispose of that waste at Hanford.
- Any fate and transport modeling used to demonstrate protectiveness should be conducted in a manner that uses the same assumptions as those in the TC & WM EIS and must be reviewed and approved by Ecology and our expert review groups.
- FFRDC must be able to document and explain the difference between any cost estimates associated with recommended options and previous cost estimates from the TC&WM EIS.
- Consider implementing technetium-99 and iodine removal from LAW prior to immobilization in order to minimize the risk posed by long-lived mobile constituents.

Specific Responses to FFRDC Questions

***Note**: Numbering of the questions posed below is for convenience only and is not intended to imply the relative importance of any question or set of questions. All of the questions seek information important to informing the FFRDC's follow-on report to Congress, as mandated under NDAA 2021. Further, when used below, the term "secondary waste" means any waste resulting as a by-product from treatment of Hanford tank waste from DSTs and SSTs.*

Questions on Selection of Disposition Alternative(s) for SLAW:

1) What does Ecology view as the 3-4 most important criteria for selection of an acceptable alternative for SLAW treatment and disposal, why, and on what regulatory basis or bases?

ECOLOGY RESPONSE:

At the outset, it is important to note that the Tri-Party Agreement Milestone M-062 requires vitrification of "Hanford High Level (HLW) and Low activity (LAW) Tank Wastes."

As discussed in detail in Ecology's answer to Question No. 14 below, the applicable RCRA LDR treatment standard for Hanford's tank waste is HLVIT. Because USDOE's 435.1 Waste Incidental to Reprocessing (WIR) process is governed by internal DOE orders pursuant to DOE's authority under the Atomic Energy Act (AEA), and not pursuant to RCRA, DOE's issuance of a final WIR Determination does not extinguish the RCRA LDR treatment standard of HLVIT. Thus, waste subject to a final WIR Determination can be disposed of as mixed low-level waste (MLLW) for AEA and Nuclear Waste Policy Act (NWPA) purposes (*i.e.*, disposed in a location other than a deep geologic repository).

But it is Ecology and EPA's longstanding position that a WIR Determination is not a RCRA decision and does not affect any pre-existing RCRA regulatory requirements. Thus, if disposal is to occur at Hanford, SLAW must be vitrified as required by the TPA and RCRA.

In terms of minimum performance criteria, Ecology considers the following factors to be important:

- The waste form must adequately protect the groundwater to meet drinking water standards and be protective to the "inadvertent intruder" (a person who engages in intrusive activities that are not expected as part of the reasonably anticipated land use). This analysis must consider cumulative impacts from other sources of contamination at the Hanford site.
- The waste form should enable DOE to minimize the land use impacts of the disposal site and must be considered reasonable and cost-effective when compared against the land use impacts and unit disposal costs associated with vitrified waste.
- The above analyses must take into account the costs and environmental impacts from all associated wastes, including but not limited to secondary waste streams.
- The waste form must perform as well as (or better than) joule-heated approaches from a standpoint of protecting human health and the environment. For groundwater this can be measured by modeling the peak concentration of waste constituents that reach the groundwater.
- If necessary to be as protective as glass, the alternative treatment must include technologies that remove/reduce the major mobile risk driver constituents prior to immobilization. These additional technologies also must be included in the total lifecycle cost estimates.

2) By what decisional process and under what "decisional framework" does Ecology recommend that a decision selecting an acceptable alternative for SLAW treatment and disposal should be made, why, and on what regulatory basis or bases?

3) What is Ecology's role in the process of selecting an acceptable alternative for SLAW treatment and disposal? What is DOE's role? What are the rationale and the regulatory basis or bases for each entity's respective role?

ECOLOGY RESPONSE:

Under the TPA, which is a legally enforceable consent order issued pursuant to CERCLA, RCRA, and the Washington Hazardous Waste Management Act, Ecology and DOE have co-equal roles in making a decision on SLAW treatment and disposal.

Because the TPA currently identifies vitrification as the required method of treatment for SLAW, DOE cannot abandon this requirement unilaterally. Under both the TPA and RCRA, changing from joule-heated vitrification to another form of treatment requires approval by Ecology.

Assuming disposal of SLAW will occur on the Hanford site, DOE will be required to obtain permit coverage under RCRA for the treatment and disposal of SLAW. In the event that DOE proposes a different treatment method for SLAW, Ecology's decision will need to be made through the permitting process, which would involve significant public input from stakeholders and the impacted communities, including tribal nations.

4) How would the responses to questions 2 and 3 above change if DOE determines under the authority of the Atomic Energy Act that some fraction of the wastes currently in the Hanford tanks is not High Level Waste?

ECOLOGY RESPONSE:

Please see Ecology's answer to Question No. 14 below.

Questions on Risk-Risk Tradeoffs Associated with Selection of Alternative for SLAW:

***Note**: For purposes of the following set of questions, the term "generally accepted national criteria" denotes a human health risk assessment basis of less than between 10^{-4} to 10^{-6} excess cancer risk or hazard quotient >1 based on the disposal scenario.*

5) How would Ecology weigh faster/earlier risk reduction via retrieval of tank waste with some fraction treated by grout, versus a much longer time frame (e.g., multiple decades additional time) to vitrify all waste and generating a much larger volume of secondary liquid waste that would have to be grouted and disposed (potentially in IDF)?

ECOLOGY RESPONSE:

At the outset, Ecology notes that it has yet to be presented with any information demonstrating that grout is indeed a quicker and cheaper pathway to treating Hanford tank wastes. This question presumes a timeline for vitrification that appears to discount the fact that a LAW melter system has already been constructed and is nearly operational at Hanford.

Moreover, the question does not appear to acknowledge the fact that grouting greatly increases the total volume of waste to be disposed when compared to vitrification. This, in turn, impacts the duration and cost of treatment and disposal and further undercuts the suggestion that grout has been shown to be—at least at this point—a significantly faster and cheaper alternative to vitrification.

Flaws in the underlying assumptions of this question aside, Ecology does consider short-term risk reductions within the broader risk analysis context, and will continue to do so. At this point, however, we have not been presented with data demonstrating that grout will significantly reduce or eliminate the short-term risks of continued storage pending vitrification, especially considering the risk of creating an orphan waste stream at Hanford in the event that grouted tank waste is ultimately rejected by the offsite disposal facility or the applicable regulatory authority. Nor have we been presented with data demonstrating that treatment shortcuts like grouting, which may or may not reduce the overall mission duration, actually outweigh the long-term risks of immobilizing tank waste in a form that is not as good as glass.

The data we have been presented with, time after time, shows the potential for significant long-term risks associated with grouting Hanford tank wastes. Indeed, environmental documentation has shown alternative treatment methods to be problematic in terms of the capability to capture dangerous constituents and hold onto those constituents over time, including, but not limited to:

- The Hanford Waste Task Force, a stakeholder advisory group, concluded that "grout doesn't adequately protect public, workers, and environment" and that "reduction of waste volume was an issue for grout" because grout increases final-waste-form volume significantly. (*Final Report of the Hanford Waste Task Force, Appendix F*, 1993)

- USDOE's 1995 waste form performance assessment identified at least three constituents (nitrate, iodine-129, and technetium-99) that would ultimately violate drinking water standards if grout is used in lieu of vitrification—both before and after the 10,000 year analysis timeframe. (*Performance Assessment of Grouted Double Shell Tank Waste Disposal at Hanford*, 1995, WHC-SD-WM-EE-004 Rev. 1)
- The 2003–2006 supplemental treatment down-select showed that cast stone (grout) would not be appropriate for LAW treatment because it would significantly impact the groundwater by releasing contaminants in concentrations above drinking water standards.

And, critically, the 2012 Tank Closure & Waste Management Environmental Impact Statement (TC&WM EIS) analyzed the impact of using grout to treat SLAW and secondary wastes associated with the Waste Treatment Plant (WTP). In doing so, the TC&WM EIS again confirmed that using grout as supplemental treatment for SLAW would allow waste constituents to reach the groundwater in concentrations that significantly exceed drinking water standards for technetium, nitrate, and chromium—even assuming inclusion of a technetium removal system prior to grouting, which DOE has since moved away from thinking about using.

In contrast, alternatives in the TC & WM EIS that assumed vitrification of primary waste and grout for secondary waste did not predict impacts above drinking water standards, and any predicted impacts to groundwater came from the grouted secondary waste, not the vitrified primary waste. While the TC & WM EIS identified that mitigation measures for the impacts of grouted secondary waste could be attempted—including a specific high performing grout, technetium removal prior to treatment, and "getters" mixed into the grout to bind specific constituents—many of these mitigation actions have not been proven.

These results show that grout is not "as good as glass" and not protective of the groundwater at Hanford.

6) How does Ecology weigh short-term operational risks versus long-term residual risks? At what point are increased operational risks to workers or the environment justified to reduce long-term residual risks significantly below generally accepted national criteria?

ECOLOGY RESPONSE:

Please see Ecology's answer to Question No. 5.

7) If near terms actions can be taken to significantly accelerate risk reduction and produce residual risk levels less than nationally accepted standards, what technical factors would preclude Ecology from supporting such alternatives?

ECOLOGY RESPONSE:

Please see Ecology's answer to Question No. 5.

8) Given the myriad of uncertainties, how important is it to have a "complete solution" versus making near-term significant progress that provides flexibility for overall tank waste treatment? For example, would a delay of 20 years or more be acceptable if the treatment delay is caused by a large-scale capital construction project, rather than piloting or taking a modular approach for promising treatment approaches for demonstration purposes? To what extent would it be helpful to use field monitoring of performance of the waste form in

the waste disposal system for a limited time frame (e.g., 5-10 years) to verify the efficacy of environmental performance models?

ECOLOGY RESPONSE:

Current Analysis of Alternatives (AOA) approaches do not show that the end of life or mission duration is any sooner on modular approaches as compared to the baseline scenario, which is what is currently required by a judicial Consent Decree. The AOA alternatives that involve grouting and modular approaches also show that the life cycle cost is the same or greater than many of the vitrification options. When compared to the baseline, these alternatives do not actually cost less or shorten the overall mission.

DFLAW is on track to start treating tank waste in 2023 and DOE's plan still indicates HLW Vitrification starting in the early 2030's, so neither Ecology nor DOE is anticipating the 20 year delay used as an example in this question. There may be a delay in pretreatment capacity coming online according to DOE, but that delay in beginning sludge washing would also delay the need for SLAW treatment capacity.

9) If a fraction of the low activity waste stream is not classified as high level waste, does Ecology see the need for more stringent standards than generally accepted national criteria? If so, why and on what regulatory basis or bases?

ECOLOGY RESPONSE:

Please see Ecology's answers to Questions 14, 16, and 17.

Questions on Non-Vitrification Alternatives for SLAW:

10) What does Ecology mean by "as good as glass" with respect to a non-vitrification waste form for SLAW tank waste?

a) What performance standards (or other measures) would need to be met in order for a non-vitrification waste form for tank wastes to be considered "as good as 'glass'"?

b) Because borosilicate and other glasses developed for disposal can vary significantly with respect to performance during disposal (i.e., known to alter and corrode/leach significantly differently in potential disposal environments), what are the specific technical and regulatory requirements that Ecology would apply to alternative waste forms for SLAW treatment (TPA Milestone M-062-40) for shallow land burial at the Hanford Site (e.g., in the IDF)?

ECOLOGY RESPONSE:

Between 2003 and 2006, facing a push by DOE to consider something other than vitrification for LAW, Washington State agreed to participate with DOE in considering alternative treatment approaches for SLAW as long as the performance of alternatives was "as good as glass."

Similarly, USDOE stated that its goal was to identify alternative approaches that: (1) could be accomplished in a shorter timeframe; (2) were more cost-effective; and (3) would perform as well as vitrification. This exploration of potential alternatives was intended as an augmentation to LAW vitrification, not as a replacement for it, and was targeted specifically at what we now

consider SLAW. The effort, generally referred to as the 2003-2006 supplemental treatment down-select, resulted in several outputs.

Pertinent to your question, this down-select process defined what constitutes "as good as glass." As then-USDOE Office of River Protection Manager Roy Schepens stated in 2003, "as good as glass" means that:

> *"The waste form resulting from treatment must meet the same qualifications of those imposed for the expected glass form produced by the Waste Treatment Plant (WTP). We expect all waste forms produced from any supplemental technology to: (1) perform over the specified time period as well as, or better than WTP vitrified waste; (2) be equally protective of the environment as WTP glass; (3) meet LDR [land disposal restrictions] requirements for hazardous waste constituents; (4) meet or exceed all appropriate performance requirements for glass, including those identified in the WTP contract, Immobilized Low Activity Waste (ILAW) Interface Control Documents, and ILAW Performance Assessment."*

Ecology agrees with this definition and maintains that any alternative treatment approach must satisfy those four threshold criteria in order to be viable.

Ecology believes it is important to note the outcome of this down-select effort here. The 2003-2006 supplemental treatment down-select process examined a suite of technologies that might meet the "as good as glass" standard in treating LAW. In the end, however, no viable approaches were identified.

The down-select showed that cast stone (grout) would not be appropriate for LAW treatment because it would result in concentrations of hazardous substances above drinking water standards in the groundwater, thus not meeting the agreed-to definition of "as good as glass."

Finally, in reference to performance standards, the 2003-2006 supplemental treatment down-select used ILAW reference glass as the comparison model. In 2012, a similar reference glass was used for the Tank Closure and Waste Management EIS. If this comparison was performed again today, these same reference glasses could be used. Alternatively, glasses modeled in the ILAW Performance Assessment could also be used as they all perform similarly in fate and transport modeling.

11) If a cementitious waste form were demonstrated to reliably produce an acceptable waste form (i.e., uncertainty quantified and acceptable), how would Ecology view the acceptability of onsite disposal of larger monoliths (i.e., analogous to saltstone disposal units at Savannah River Site) if they would improve long-term reliability and environmental performance?

ECOLOGY RESPONSE:

This alternative has previously been posed to Pacific Northwest communities (tribal nations as well as stakeholders in the Tank Waste Task Force) and was rejected.

As noted in Ecology's answer to Question No. 10, there are outstanding concerns over grouted waste forms in general. Larger grout monoliths present additional problems, including but not limited to:

1. The large number of grout vaults needed for grout monoliths, with associated land use impacts.
2. Inability to achieve full solidification of larger grout forms.
3. Retrievability of grouted monoliths from the disposal facility in the event of waste form failure.

12) How would Ecology view offsite grouting of SLAW at a commercial facility, either in Washington state or another state?

a) If offsite grouting of tank waste were to be done in Washington state at a permitted MLLW treatment facility, what permit conditions, if any, does Ecology believe would need to be added to the receiving treatment facility's RCRA permit, why and on what technical and regulatory basis or bases?

b) If offsite grouting of tank waste were to be done in another state at a permitted MLLW treatment facility, what, if any, permit conditions does Ecology believe would need to be added to the Hanford RCRA permit, why, and on what technical and regulatory basis or bases?

ECOLOGY RESPONSE:

It is hard to discuss what permit conditions would be needed for an offsite treatment facility without being provided a permit application and full design. There would be many permit conditions to regulate the construction, operation, and closure of the facility. Please see Ecology's answers to Question Nos. 14, 16, and 17 below.

By way of further answer, Ecology notes that tank waste solidified into a grout matrix will not be able to meet waste acceptance criteria at any landfill disposal facility in the State of Washington, whether on or off the Hanford site. Assuming that any such waste will be disposed out of state, grouting of tank waste may be appropriate depending on the disposal facility's geology and waste acceptance criteria. Indeed, the objective of the Test Bed Initiative is to explore the technical and regulatory feasibility of that very alternative.

13) Between grout and steam reforming, which would Ecology prefer for SLAW treatment? On what specific factors/criteria is this preference based?

ECOLOGY RESPONSE:

The answer to this question can only be derived after a robust, transparent, and peer reviewed down-select process that involves substantial opportunities for public engagement.

Questions on Acceptable Waste Forms for Secondary Waste:

14) What are Ecology's views about which waste forms are acceptable for secondary waste, why and on what regulatory basis or bases? As indicated in question 4 above, how would these views change if DOE determined that some of the tank waste was not High Level Waste?

ECOLOGY RESPONSE:

"Secondary Waste" is a broad term that can include waste streams from a number of sources. For purposes of this response, Ecology assumes that you are referring specifically to secondary waste generated during the vitrification of Hanford tank wastes.

Determining the acceptable waste form for this secondary waste requires a fact-specific analysis. It is, therefore, difficult to draw conclusions about acceptable waste forms that would apply to all secondary waste that might be generated during the vitrification of Hanford tank wastes.

That said, Ecology does not take the position that the HLVIT standard will apply as a matter of course to secondary waste generated by the vitrification process. The WTP permit does not identify the HLVIT treatment standard as applying to this secondary waste and does not require vitrification of this secondary waste prior to land disposal. Instead, the permit requires DOE to develop documents identifying all secondary wastes, the constituents in those wastes, and how those wastes will be treated.

With these caveats, some general observations on the legal frameworks governing secondary waste treatment and disposal can be made that may be helpful to your analysis.

A foundational principle of RCRA is that treatment standards attach to hazardous waste at the point of generation and remain attached until the treatment standard is met. Moreover, all wastes derived from a listed hazardous waste remain a hazardous waste unless otherwise excluded by RCRA. This is RCRA's fundamental "cradle to grave" promise, and it exists to ensure a conservative and cautious approach is taken with regard to even treated wastes that may continue to pose a threat to human health and the environment. As a result, exceptions to these general principles are narrow.

One of these narrow exceptions occurs under what is referred to as a change in "treatability group" applicable to characteristic wastes. Under this exception, if a treatment process creates a different waste form (e.g., a sludge results from concentrating the solids entrained in a liquid waste), the resulting waste can constitute a new point of generation subject to the treatment standard applicable through an analysis of the newly-generated waste's own characteristics rather than that of its source.

Critically, however, EPA has made clear that this determination must look "to the entire treatment process, not to each component part." 64 Fed. Reg. 25,408, 25,421 (May 11, 1999). Thus, in general, "the determination of whether a new hazardous waste is generated—i.e., whether a new point of generation for LDR purposes is created—is made at the *completion* of the treatment process." *Id.* (emphasis added). As a result, RCRA creates a dichotomy between: (1) wastes resulting from final treatment, potentially allowing for a new treatment standard to attach to treatment residuals; and (2) wastes resulting from an incomplete or intermediary treatment step and that are still bound by the original treatment standard.

With reference to Hanford, tank wastes were "generated" in 1987 when RCRA became applicable at the Hanford site, and the "HLVIT" (vitrification) treatment standard attached to tank wastes in 1990 when EPA adopted the "third third" rule. Tank wastes are "non-wastewaters" and contain both listed and characteristic wastes.

Applying the aforementioned RCRA rules to the treatment of tank waste, wastes that result from an interim tank waste treatment step (for example, the liquid resulting from filtration and tank-side cesium removal) retain the original tank waste's designation and applicable treatment standard (HLVIT) because further steps in the treatment train are still necessary. Assuming the change in treatability group rule is met, however, secondary wastes that result from the end of a treatment train (for example, wastes generated during vitrification of tank waste at WTP) may qualify as newly generated wastes and the HLVIT standard (or indeed *any* treatment standard) may not apply, depending on how those wastes designate under RCRA. Other sources of secondary wastes, such as "debris" as defined in 40 C.F.R. § 268.2(g), may also qualify for treatment standards separate from that of the tank wastes.

It is important to note that these requirements, and thus Ecology's views on RCRA treatment standards, do not change solely based on whether DOE determines that tank wastes are not high-level waste. DOE's radiological waste classification process under DOE Order 435.1 is separate and distinct from the dangerous waste designation process under RCRA. The 435.1 WIR process is governed by internal DOE orders pursuant to DOE's AEA authority and not pursuant to RCRA. Accordingly, DOE's issuance of a final WIR Determination does not extinguish the RCRA LDR treatment standard of HLVIT. Thus, waste subject to a WIR determination can be disposed of as MLLW for AEA and NWPA purposes (*i.e.*, disposed in a location other than a deep geologic repository), but it is Ecology and EPA's longstanding position that a WIR determination does not affect any RCRA regulatory requirements.

This position is supported by DOE's Order 435.1 implementing manual and guidance, which recognize that DOE must manage waste in accordance with the requirements of both RCRA and Order 435.1. In DOE Order 435.1 Implementation Guide (rescinded in 2021 associated with administrative changes to DOE Order 435.1), DOE acknowledged the basic RCRA principle that the HLVIT LDR treatment standard has attached to high-level wastes, regardless of a DOE WIR determination:

> *"*The Environmental Protection Agency has determined that vitrification (HLVIT) is the best demonstrated available technology (BDAT) for treating high-level wastes that exhibit these characteristics. However, if additional characteristic waste codes become applicable to the high-level waste, e.g., D018: benzene, the treated high-level waste may need to meet the Universal Treatment Standards (40 CFR 268.48) for any underlying hazardous constituents (UHCs). *A treatability variance (40 CFR 268.44) and/or determination of equivalent treatment (40 CFR 268.42(b)) may be necessary to fully comply with the LDR standards if a DOE site elects to use a technology other than vitrification, the BDAT, of if it is impractical to comply with all the standards applicable to individual waste codes." (Emphasis added.)*

Although DOE's issuance of a final WIR Determination does not extinguish the LDR treatment standard under RCRA, Ecology believes that such a determination is necessary to support Ecology's consideration of a treatability variance for any non-vitrified tank waste to be disposed of at Hanford, including for any tank waste residuals that will remain in place as part of landfill closure of the tank farms. In particular, Ecology believes documentation that the waste can be legally managed as LLW under the AEA and NWPA is necessary to support a determination under 40 C.F.R. § 268.44(h)(2)(i) that treatment by vitrification is "technically inappropriate."

15) What is the required performance basis for the secondary waste form for disposal in the IDF?

16) What is the regulatory status and permitting framework for grout treatment (e.g., cast stone) of secondary waste from Direct Feed LAW vitrification (DF LAW) and disposal at Hanford in the Integrated Disposal Facility (IDF)? Do the waste forms that are acceptable for secondary waste differ from those waste forms that are acceptable for primary SLAW waste? If so, what are the technical and regulatory bases for differentiating the waste form for secondary versus primary waste?

ECOLOGY RESPONSE:

As described above, because secondary waste from DFLAW comes at the end of the tank waste treatment train, some of that waste may qualify as a new point of generation to which the HLVIT standard would not apply, again assuming applicability of the change in treatability group principle. The same is not true of *Supplemental* Low Activity Waste (SLAW) because removing SLAW from the tanks—even with pretreatment—is an interim, not final, step in the treatment train. In other words, because pretreatment is an intermediate step on the way to HLVIT, LAW is not a newly generated waste for RCRA purposes. A new point of generation, therefore, has not been established and the derived from rule requires that SLAW retain the treatment standard of the wastes from which it originated, in this case HLVIT.

As both Ecology and EPA have repeatedly stated, this does not mean that LAW cannot be treated with a standard other than HLVIT. The regulatory authority for the ultimate disposal site can potentially issue a site-specific treatability variance under 40 CFR § 268.44(h) (assuming treatment to satisfy LDR standards for any waste codes other than D002 and D-004-D011 is also accomplished). EPA can potentially issue a determination of equivalent treatment under 40 C.F.R. § 268.42(b) or a no-migration petition for the disposal site under 40 C.F.R. § 268.6.

Questions on Authority to Determine Whether or Not SLAW Tank Wastes are High Level Wastes (HLW):

17) Based on what rationale and regulatory/legal basis does Ecology assert that the RCRA mixed wastes in the Hanford tanks were or are HLW?

a) Is Ecology's assertion based on a regulatory determination or determinations by Ecology? If so, what specific regulatory determination has Ecology made, and on what regulatory basis or bases?

b) Is Ecology's assertion based on Ecology's conclusion that DOE has made a determination that the tank wastes are HLW? If so, on what rationale and regulatory basis or bases does Ecology base its conclusion that DOE has made a determination that the tank wastes are HLW? Specifically, does Ecology conclude that DOE made a determination of HLW for the tank waste based on DOE's past management of such wastes as HLW, and if so, which aspects of past management? Also, specifically, does Ecology conclude that DOE made a determination that the tank wastes are HLW based on the past filing a RCRA Part A (and/or other RCRA regulatory actions) with respect to the tanks?

c) Are there additional or alternative rationale(s) and legal/regulatory bases for Ecology's assertion that the tank wastes are HLW?

ECOLOGY RESPONSE:

The question of whether RCRA mixed wastes in the Hanford tanks are HLW is not a regulatory decision made by Ecology. Rather, it is a question of federal law determined by Congress.

The AEA and NWPA both define HLW as "the highly radioactive material resulting from the reprocessing of spent nuclear fuel," including "liquid waste produced directly in reprocessing" and "any solid material derived from such liquid waste that contains fission products in sufficient concentrations" to require deep geologic disposal. 42 U.S.C. § 10101(12). This has long been widely understood and referenced as a "source based" definition; i.e., material generated from the reprocessing of spent nuclear fuel is, by definition, HLW. Under this understanding, the definition's reference to "highly radioactive material" is simply descriptive. If material results from reprocessing, it *is* "highly radioactive."

Consistent with this view, Washington State has long maintained that the federal and state regulatory framework provides two principal ways by which material "resulting" from reprocessing may be reclassified as something other than HLW. The first is if the material's source origin is so far removed from direct reprocessing activity that it can be fairly declared to not "result" from reprocessing; i.e., to be "waste incidental to reprocessing" (WIR). The second is if solid material derived from liquid reprocessing waste no longer contains fission products in sufficient concentration to require deep geologic disposal. This is the approach by which we think it is permissible for immobilized (vitrified) low activity waste to be disposed of at Hanford.

DOE's prior version of Order 435.1 roughly followed these two means of reclassifying waste, although Washington and other states have argued in the past that some aspects of the Order go beyond the bounds of the statutory definition and purport to allow DOE to reclassify HLW based on other considerations.

DOE has adopted by rule an interpretation of the statutory term that runs counter to the previous, long-held "source based" understanding of HLW (a reclassification that does not fall under one of the two reclassification options outlined above, I.e., WIR or change in concentration of fission products). We understand that DOE has already applied that interpretation to dispose of a certain waste stream generated at the Savannah River Site (SRS), and is now seeking to do so again with another SRS waste stream.

Washington State strongly disagrees with DOE's purported interpretation, and continues to reserve its right to challenge that interpretive rule as applied. At this point, however, DOE has stated publicly that it has "no intention" of applying its HLW interpretation at Hanford (Attach Letter from Ike White). Thus, Order 435.1 will continue to govern the radiological waste reclassification process for Hanford's tank wastes.

18) What is Ecology's interpretation of DOE's AEA authority to determine that untreated or treated Hanford tank waste is non-HLW? What is/are Ecology's regulatory basis or bases for this interpretation?

a) Given DOE's authority under the AEA to regulate the radioactive components of RCRA mixed waste, at what point in the history of tank waste storage/management at Hanford did or does Ecology make a determination (or otherwise decide, for RCRA regulatory purposes) as to whether RCRA mixed SLAW tank waste is High Level Waste or non-HLW, and on what regulatory authority/basis or bases? If Ecology has

already made this determination (or otherwise concluded, for RCRA regulatory purposes), at what date was this done? Has Ecology documented this determination (or other RCRA decision) regarding the HLW character of mixed tank waste at Hanford, the rationale and regulatory basis or bases for it, together with supporting documentation, in the administrative record for Hanford? If so, could you please provide these materials (and/or specific citations to them in the administrative record) to the FFRDC?

b) Does Ecology believe that any untreated or treated tank waste (or tank waste fraction) that is a "mixed" RCRA hazardous waste can be determined to be a non-HLW? If so, which tank waste, under what conditions, and what entity, if any, would need to make and/or approve the determination? If not, why not, and on what regulatory basis or bases?

c) Would Ecology accept a WIR determination made by DOE under the AEA and relevant DOE Orders as a valid basis for a determination that a given tank waste is non-HLW? If so, under what conditions and with respect to which tank wastes or tank waste fraction(s)? If not, why not, and on what regulatory basis or bases?

d) Would Ecology accept a (non-WIR) determination made by DOE under the AEA and relevant DOE orders as a valid basis for a determination that the radionuclide portion of a given RCRA mixed hazardous tank waste is non-HLW? If so, with respect to which tank wastes or fractions of tank waste? If not, why not, and on what regulatory basis or bases?

e) What was Ecology's regulatory basis for the proposed permit condition II.L.2 (excerpted below) in the draft Test Bed Initiative (TBI) Research, Development and Demonstration (RD&D) permit, specifically with regard to the statement "the HLVIT treatment standard is attached to this waste"?

> "II.L.2 Ecology has determined that the HLVIT treatment standard is attached to this waste in addition to the applicable 40 CFR 268.40 treatment standards for the dangerous waste codes other than D002 and D004-011 identified in the Double-Shell Tank Part A Permit Application, dated December 14, 2009, as modified by the TBI Phase 2 RD&D permit application submitted on May 14, 2019."

f) Please explain the statements made in Ecology's September 2021 comments on the draft Environmental Assessment for TBI Phase 2, that a DOE WIR determination (i.e., a determination made under DOE Order 435.1 that a waste is WIR and non-HLW) "does not affect any RCRA provisions" and "does not affect any RCRA regulatory requirements"? On what legal/regulatory basis are these assertions based? Please explain how these assertions align with or do not align with EPA's position (on the EPA website) that "US Department of Energy (DOE) regulate[s] the radioactive portion of mixed waste under AEA authority, while EPA regulates the hazardous waste portion of mixed waste under RCRA authority." If Ecology's position does not align with EPA's, what are the rationale for, and the legal/regulatory basis or bases on which, Ecology appears to be adopting a position that is different from EPA's with respect to this issue?

g) How is secondary waste classified in terms of the level of radiological activity, by whom, and on what regulatory basis or bases? Is it assumed that secondary waste will likely meet waste incidental to reprocessing (WIR) criteria?

ECOLOGY RESPONSE:

In terms of DOE's regulatory authority to determine that tank waste is non-HLW, please see Ecology's response to Question No. 17. As noted, Ecology can accept—and indeed *has previously accepted*—WIR determinations made by DOE under relevant DOE orders as a technical basis to support Ecology's determinations that certain mixed wastes can be managed as non-HLW under RCRA.

The WIR process set forth in DOE Order 435.1 remains the process applicable at Hanford, and Ecology will continue to oppose any efforts to reclassify HLW by other means unless and until they are demonstrated to be more protective than the existing process. In terms of the substance of pending WIR determinations, these determinations and their supporting documentation will continue to be evaluated on a case-by-case basis, and Ecology does not believe it is prudent to make broad statements in the abstract about the appropriate conditions under which to do so.

In terms of your questions regarding TBI and prior Ecology statements, please see Ecology's response to Question No. 14. Furthermore, and as noted, EPA shares Ecology's view that WIR determinations do not impact RCRA LDR requirements and that DOE's position otherwise is inconsistent with long-established principles under EPA's RCRA LDR program. As Ecology and EPA have repeatedly identified, RCRA has multiple pathways by which pretreated HLW managed as MLLW (including TBI wastes) can be disposed in an appropriate near-surface disposal facility without meeting the HLVIT treatment standard.

Finally, in terms of secondary waste classification, please see Ecology's response to Question No. 14. By way of further answer we note that, while such determinations are highly fact-specific, Ecology anticipates that secondary wastes from WTP will likely meet WIR criteria.

Questions on RCRA Land Disposal Restrictions Applicable to SLAW:

19) In Ecology's view, what is the "point of generation" for purposes of determining the applicability of RCRA LDR standards to Hanford mixed RCRA hazardous tank wastes/ SLAW containing RCRA mixed wastes, and as of what date did (or does) that point of generation arise?

a) On what regulatory basis or bases does Ecology base its determination of the point of generation, and the date as of which the point of generation arises, with respect to Hanford mixed RCRA tank wastes/SLAW, for LDR purposes?

b) On what regulatory basis or bases does Ecology characterize the radioactive portion of the tank waste (e.g., as HLW, non-HLW, etc.) for RCRA LDR purposes, given DOE's authority under AEA to regulate the radioactive components of RCRA mixed waste?

c) Given DOE's AEA authority to regulate radioactive components of Hanford mixed RCRA tank waste/SLAW, are there separate points of generation for the radioactive and non-radioactive components of such mixed waste for RCRA LDR purposes? If so, for RCRA LDR purposes what would the points of generation be for radioactive and non-radioactive components of such waste, respectively, and when would such points of generation arise? If not, why not and on what regulatory basis or bases?

d) Does Ecology believe that a new point of generation for RCRA LDR purposes with respect to Hanford mixed RCRA hazardous tank waste/SLAW may later occur (i.e.,

subsequent to the original point of generation) for either or both radioactive and non-radioactive components of such waste? If so, under what circumstances and on what regulatory basis or bases? If not, why not and on what regulatory basis or bases?

ECOLOGY RESPONSE:

Please see Ecology's answer to Question Nos. 14, 16, and 17.

20) Would Ecology consider a petition/application from DOE for RCRA LDR variances/exceptions/no migration petitions with respect to the RCRA LDR treatment/standard applicable to Hanford mixed tank wastes/SLAW?

a) If so, which type(s) of variance, etc., if any, might Ecology consider, why and on what regulatory basis or bases?

b) Which type(s) of variance, etc., if any, would Ecology not consider, why not and on what regulatory basis or bases?

c) If Ecology would consider an "equivalent treatment" variance under RCRA, what exactly would DOE need to demonstrate in order for the variance to be approved by Ecology, and what specific requirements/standards would need to be met?

d) With respect to a site-specific treatability variance under 40 CFR 268.44(h), would Ecology accept a site-specific treatability variance approved by the state regulator in the disposal state if the disposal state and its regulator were the states of Texas or Utah? If so, under what conditions, with respect to which wastes, and on what regulatory basis or bases? If not, why not and on what regulatory basis or bases?

ECOLOGY RESPONSE:

As a regulator, Ecology will consider any requests properly submitted by regulated entities pursuant to its authority under the HWMA and its delegated authority under RCRA, including applications for treatability variances, "no migration" petitions, or determinations of equivalent treatment. Please note, however, that Ecology does not have a regulatory role in approving site-specific treatability variances (or other modifications to treatment standards) for wastes that will be land disposed in other states. That decision would be made by the local EPA Region and/or authorized state.

For Hanford tank wastes destined for out-of-state disposal, Ecology's role would be limited to permitting any related waste management activities occurring in Washington, including retrieval and pretreatment activities. This permitting process involves identifying the waste codes and corresponding LDR treatment standards that attached to the waste prior to such retrieval and pretreatment, in order to ensure those waste management activities are performed properly based on the waste's designation.

That said, Ecology remains concerned about the possibility that wastes purportedly destined for disposal in other states will become, instead, stranded at the Hanford site if not ultimately accepted by the state(s) to which they are sent.

If DOE chooses to use the Hanford site or another facility located in Washington State (such as Perma-Fix Northwest) to grout its TBI wastes, Ecology would have a regulatory role with regard to permitting those grouting activities. However, the decision to perform these grouting activities in Washington State would increase the risk of creating an orphan waste stream that would

remain at (or return to) Hanford in the event it is rejected by the disposal site or its regulatory authority. Accordingly, Ecology reserves the right to use its regulatory authority to impose permit conditions to ensure that wastes treated in Washington State, but destined for disposal elsewhere, will actually meet waste acceptance criteria and other disposal requirements in the disposal state(s).

21) Does Ecology believe that use of the following non-vitrification waste forms for Hanford mixed RCRA tank wastes/SLAW could be compliant with RCRA LDR requirements? If so, under what conditions, with respect to which wastes, and on what regulatory basis or bases? If not, why not and on what regulatory basis or bases?

a) Grout

b) steam reforming

ECOLOGY RESPONSE:

Please see Ecology's responses to Questions No. 14, 16, and 17. As noted, non-vitrified waste forms for Hanford tank wastes (including SLAW) may be compliant with RCRA LDR requirements under certain conditions, but only if subject to approvals from the receiving state(s) and/or EPA. That said, Ecology notes that—at least at Hanford—RCRA and other applicable statutes are not the only governing factor.

Current Tri-Party Agreement milestone language for Supplemental Treatment assumes a vitrification-type facility will be used to treat SLAW. For example:

- M-062-40 requires the System Plan to "outline specific options to treat all the LAW" and provides two such options: (1) construction of a "2nd LAW vitrification facility" and (2) construction of a "Bulk Vitrification Facility."
- Milestone M-062-45 requires the parties to negotiate a "supplemental treatment selection" and provides that a second LAW vitrification facility "must be considered as one of the options."
- Milestones M-062-31-T01 through M-062-34-T01 require permitting, construction, and commissioning of a "Supplemental Vitrification Treatment Facility and/or WTP Enhancements."

This is not without reason. At Hanford, there are many advantages to choosing a more robust waste form for near surface disposal based on modeling that has occurred over many decades, as well as the regulatory requirement that landfills not impact groundwater. Ecology has interpreted this as prohibiting any disposal actions that would impact the groundwater above drinking water standards.

Constituents of concern in Hanford's tank waste include chromium, nitrate, uranium, technetium-99, and iodine-129. Previous modeling has shown that disposing of LAW in any other waste form than joule-heated vitrification would impact the groundwater underlying Hanford for many thousands of years, and, as a result, those waste forms are not acceptable for onsite disposal. This is particularly important given the additional waste burden that already exists in Hanford soils and groundwater. It is unacceptable to add to that burden by disposing of grouted tank waste in a near surface landfill located above an abundant and protective aquifer that feeds the Columbia River, a tremendous natural resource for the entire Pacific Northwest.

Ecology's agreement to the current tank waste treatment pathway was based on DOE's long-held promise of vitrification for this tank waste. If the treatment is not going to be vitrification or its equivalent, Ecology would have to reconsider the acceptability of on-site disposal.

Questions on Onsite Disposal of SLAW at Hanford:

22) Do Ecology's views on the acceptability of onsite disposal in IDF differ for:

a) grouted SLAW tank waste?
b) secondary waste from vitrification?
c) steam reformed SLAW?

If so, what are the differences and on what specific regulatory and/or technical grounds are the differences based?

ECOLOGY RESPONSE:

Please see Ecology's answers to Question Nos. 14, 16, and 17.

23) To what degree would retrievability of the SLAW treated waste form be valued by Ecology, and if so, why and on what regulatory basis?

24) The IDF Permit requires a risk budget tool; with respect to disposal risks associated with onsite disposal of SLAW:

a) Does Ecology see a need to differentiate nitrate/nitrite, technetium, and iodine in, respectively, grouted secondary waste, grouted primary SLAW, and SLAW steam reformed product, with respect to risks? If so, what are the regulatory and technical bases for differentiating these waste constituents with regard to the different SLAW alternatives?
b) If there are different environmental or human health risks for onsite disposal at the Hanford Site of secondary waste grouts versus SLAW grout, has Ecology evaluated and compared the risks from these two types of waste in a written document, and would it be willing to provide the document to the FFRDC? Have the risks from these two types of waste been independently evaluated, and if so, by whom and in what document?

Questions on Offsite Disposal of Hanford SLAW:

25) What is Ecology's View of offsite Disposal of Hanford SLAW? Would Ecology's views on offsite disposal be different if the material being sent offsite for disposal were:

a) steam reformed SLAW? Versus
b) grouted SLAW?

If so, what are the differences, and on what regulatory and technical grounds are the differences based?

ECOLOGY RESPONSE:

Please see Ecology's answers to Question Nos. 14, 16, and 17.

26) Specifically, what is Ecology's view of disposal of SLAW in a grouted waste form onsite at IDF versus disposal of SLAW in a grouted waste form offsite at a licensed commercial MLLW facility? On what regulatory and technical bases are Ecology's views based?

ECOLOGY RESPONSE:

Please see Ecology's answers to Question Nos. 14, 16, and 17.

Questions Regarding Releases Associated with, and Permitting Related to SLAW Disposition:

27) What is Ecology's assessment of the following release and permitting issues associated with SLAW disposition:

Offsite Disposal of SLAW:

a) If Hanford SLAW were to be disposed offsite, would any permit conditions need to be added to the Hanford RCRA Permit—and if so, what would those permit conditions be, and on what regulatory and technical bases-- if the waste being sent offsite for disposal were:

   i) steam reformed SLAW? Versus

   ii) grouted SLAW?

ECOLOGY RESPONSE:

Please see Ecology's response to Question No. 20.

Air Toxics:

b) Does Ecology envision any challenges with permitting for air toxics for, respectively, a grout facility, steam reforming facility or vitrification facility? If so, what are the challenges, and how do these SLAW alternatives compare with respect to these challenges?

c) What is Ecology's assessment of the risks to human health and the environment associated with air toxics releases from, respectively, SLAW vitrification, grout, and steam reforming, what are the primary risks from each of these SLAW alternatives, and on what data is Ecology's assessment of air toxics risks based?

d) Specifically, with respect to SLAW and/or LAW vitrification, does Ecology have one or more document(s) providing the results of its assessment of air toxics releases and resulting risks associated with SLAW and/or LAW vitrification? If so, would Ecology be willing to share such document(s) with the FFRDC? If not, please explain.

ECOLOGY RESPONSE:

Ecology's NWP Air Permitting Project is currently processing and anticipates receiving additional Notice of Construction applications specifically related to or supporting the operation of DFLAW. Project personnel are actively reviewing the applications for completeness and cannot pre-determine or speculate as to potential challenges with permitting for air toxic emissions before those reviews are completed, much less for an application not received as of yet.

Water/Wastewater:

e) Does Ecology envision any challenges with permitting for water/wastewater discharges, respectively, for a grout facility, steam reforming facility or vitrification facility for SLAW?

ECOLOGY RESPONSE:

At this time Ecology anticipates non-contact wastewater streams generated by processes at WTP are planned for discharge at the Treated Effluent Disposal Facility (TEDF). Wastewaters from WTP that require treatment at the 200E Area Effluent Treatment Facility are anticipated to be discharged at the State Approved Land Disposal Site (SALDS). Wastewater discharge permits for TEDF and SALDS are undergoing a permit renewal process and will incorporate any necessary modifications to ensure discharges are in compliance with state and federal requirements.

f) What are the primary water/wastewater risks to human health and the environment from each alternative technology and how do the alternatives compare with one another with respect to such risks?

ECOLOGY RESPONSE:

Ecology has not determined what risks would be posed by alternative technologies or what wastewaters would be generated by alternative technologies.

Grout Facilities:

g) What are Ecology's views on the regulatory challenges for permitting an onsite grout facility? Do these permitting challenges differ as between permitting a centralized grout facility versus permitting multiple smaller grout facility units associated with specific tank farms?

ECOLOGY RESPONSE:

Ecology anticipates a Class 3 permit modification would be required to permit an onsite grout facility. Two public comment periods would be required and a conservative estimate for issuance would be 12-18 months.

Permitting multiple smaller grout facility units would still most likely require a Class 3 permit modification, but the multiple units could most likely be incorporated through a single modification. Depending on the design and technical review (e.g., any differences in design among the grout facility units), the issuance timeframe could be reduced or extended.

h) Would the permitting challenges noted in g), above, require different permitting strategies for permitting a centralized grout facility versus permitting multiple smaller grout units? If so, what would those strategies be, why, and on what regulatory and technical bases?

ECOLOGY RESPONSE:

Ecology anticipates both options would require a Class 3 modification.

"Take Back" provisions:

i) Please explain the rationale, as well as the regulatory and technical basis, for "take back" provisions with respect to Hanford tank waste sent offsite for dispositioning (e.g., treatment and/or disposal). Under what circumstances are take back provisions applicable to offsite dispositioning of treated and untreated: RCRA hazardous waste; RCRA mixed waste; and/or radioactive waste, respectively, and on what technical and regulatory bases?

Onsite Transportation of SLAW Issues:

28) What are Ecology's views on the transportation of SLAW to the immobilization facility (vitrification or grout or steam reforming) onsite through:

a) short distance to a modular facility?
b) cross-site transfer pipeline?
c) load-out to a transport conveyance followed by transport via trucking or rail line?
d) Are any of the above onsite transportation methods preferable to other methods, and if so, why and on what technical and regulatory basis or bases?

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Appendix K. Disposal Site Responses to FFRDC Team Questions

The Federally Funded Research and Development Center (FFRDC) team developed a set of questions addressed to the Energy*Solutions* Clive Facility and Waste Control Specialists, LLC to help better understand how off-site disposal of Hanford supplemental low-activity waste (LAW) at these facilities could advance the Hanford supplemental LAW treatment mission. The responses to the NDAA-3125 team's questions are attached as they were received from each facility.

Energy*Solutions* Clive Facility Responses to FFRDC Questions regarding Regulatory Issues on the Report on Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation

From: Scott Dempsey
To: Kalinina, Elena
Cc: Ammerman, Douglas J; Johnny Bowne
Subject: RE: Congressionally-Directed Study of Hanford LAW Disposal Solutions
Date: Tuesday, September 7, 2021 8:06:25 AM
Attachments: EnergySolutions Capability to Treat and Dispose of Hanford Liquids.pdf

Good Morning Ms. Elena. I hope you had a safe and enjoyable holiday weekend. I was on business travel last week and a bit delayed in getting you the information you requested. We have provided a good bit of information regarding our pricing and capabilities to the Government Accountability Office and believe it is best for you to contact them directly for that information as follows:

Courtney S. Tepera, Analyst
Government Accountability Office
Atlanta Field Office l 2635 Century Parkway, Atlanta, GA 30345 l [redacted] l teperac@gao.gov

In regards to what we can receive at our facilities… The following volumes identifies the amount of waste received per year in Cuft at our Clive, UT and Oak Ridge, TN facilities. We would also like to identify that we received $16.3M Cuft in 2006 due to increases primarily from DOE projects.

Total Gate Receipts	
Clive	CUFT
2017	6,063,299
2018	6,498,301
2019	5,381,325
2020	1,519,910
2021	885,869

BCO Gross Cuft

Row Labels	**Gross CUFT**
2017	2,352,467.6
2018	2,316,372.2
2019	2,001,368.4
2020	1,850,156.8
2021	1,068,857.4
Grand Total CUFT	**9,589,222.5**

Lastly, the attached was provided as general information to EM representatives in Washington, DC, is general knowledge, and can be shared with your team. Please let me know if you have need any additional information. We are looking forward to supporting the team in the evaluation of various options.

From: Kalinina, Elena [mailto:eakalin@sandia.gov]
Sent: Monday, December 13, 2021 7:04 PM
To: Scott Dempsey <sjdempsey@energysolutions.com>
Subject: [EXTERNAL] A Few Questions Related to Disposal

Scott:
I hope to get the waste volume and waste composition data for the different off-site alternatives from the new calculations soon. I would like to check with you on a few things that are important for the transportation and disposal analysis. I wonder what is the total waste volume and total Ci content that can be used for the disposal of the Hanford waste at the Clive site? What is the maximum monthly volume that can be accepted? Please let me know of any other limitations that we should consider.

Best regards.

Elena

From: Scott Dempsey <sjdempsey@energysolutions.com>
Sent: Wednesday, December 15, 2021 9:37 AM
To: Kalinina, Elena <eakalin@sandia.gov>
Subject: RE: [EXTERNAL] A Few Questions Related to Disposal

Good Morning Ms. Elena. I am checking with our site to respond to your request. I hope to have that shortly. Do you know how many gallons that will be Class A after the Cesium and Strontium is removed?

From: Kalinina, Elena [mailto:eakalin@sandia.gov]
Sent: Wednesday, December 15, 2021 12:12 PM
To: Scott Dempsey <sjdempsey@energysolutions.com>
Subject: RE: [EXTERNAL] A Few Questions Related to Disposal

Scott:
The total waste volume assumed in 2018 was 54 million gal times 1.8 (coefficient for grouted waste) or times 1.2 (coefficient for steam reformed waste). This translates in 369,000 cub m (grouted waste) or 246,000 cub m (steam reformed waste). I expect to see similar total volumes with ~90% type A waste when I get the new data. Part of type A waste can go to WCS.

Thank you.

Elena

From: Scott Dempsey
Sent: Monday, December 20, 2021 11:43 AM
To: Kalinina, Elena <eakalin@sandia.gov>
Subject: RE: [EXTERNAL] A Few Questions Related to Disposal

Good morning Ms. Elena. I hope you are well and getting ready for a safe and enjoyable Christmas break. We can receive waste up to the Class A limits for disposal. Once the waste is received we will treat and place in our cell for disposal. We don't have a limit in the total amount as it is not a cumulative or running total. We currently have over 3M cubic feet of disposal space left in our current cell. We continually monitor the volumes and will look to expand when needed. Does that provide the info you need?

Merry Christmas!

From: Scott Dempsey
To: Kalinina, Elena
Subject: RE: [EXTERNAL] A Few Questions Related to Disposal
Date: Monday, December 20, 2021 11:43:50 AM

Sorry… 3 million cubic yards, ***not*** cubic feet.

From: Kalinina, Elena [mailto:eakalin@sandia.gov]
Sent: Wednesday, January 12, 2022 6:46 PM
To: Scott Dempsey <sjdempsey@energysolutions.com>
Subject: [EXTERNAL] Disposal Cost Question

Scott:

Happy New Year!

I am back to work and I have one more question for you (and probably more to come). I wonder what is the disposal cost of the grouted waste per cubic m. The information sheet that you sent me a while ago has the cost of treatment and disposal of liquids (~$10,000/m3). I assume that the cost of disposal of grouted waste is significantly lower? A number (even approximate) would be very helpful.

Best regards.

Elena

From: Scott Dempsey
To: Kalinina, Elena
Subject: RE: [EXTERNAL] Disposal Cost Question
Date: Thursday, January 13, 2022 5:49:26 AM

Good Morning Elena,

Happy New year to you as well. The following is what we provided to the GAO regarding grouted waste with no volume commitment. This pricing would be adjusted if volumes were identified and committed to.

As requested, I am responding to your request for "budgetary pricing" for disposing of Hanford's grouted SLAW at our Clive, Utah Facility. After discussing with my colleagues, we believe it would be appropriate to utilize pricing from our existing DOE EMCBC LLW/MLLW Disposal Contract #89303318DEM000005. The appropriate pricing to be utilized for Class A LLW would fall under CLIN 1004 – Baseline Debris Disposal and include a surcharge for Oversize debris. The current Year-3 Unit Price for Class A LLW Debris is $649.94 per cubic yard and the Oversize debris surcharge would add $237.05 per cubit foot for a total of $886.99 per cubic yard (**$32.85 per cubic foot**). The Hanford grouted SLAW would be required to meet the Clive, Utah Waste Acceptance Criteria for our Bulk Waste Facility which is also attached for reference.

Please let me know if you need any additional information or have any questions or concerns. Have a great day and remainder of the week.

From: Kalinina, Elena [mailto:eakalin@sandia.gov]
Sent: Thursday, January 13, 2022 2:57 PM
To: Scott Dempsey <sjdempsey@energysolutions.com>
Subject: RE: [EXTERNAL] Disposal Cost Question

Scott:

I don't see the reference (Waste Acceptance Criteria for Bulk Waste Facility) mentioned in your email. I hope that you can send It to me.

Thank you!

Elena

From: Scott Dempsey
To: Kalinina, Elena
Subject: RE: [EXTERNAL] Disposal Cost Question
Date: Thursday, January 13, 2022 1:26:13 PM
Attachments: 89303318DEM000005.pdf
Clive BWF WAC Rev 10.pdf

Sorry about that. Didn't know you wanted that document. It is attached. Please remember we would treat the liquids at Clive to meet this requirement if the liquids are shipped directly. Grouted SLAW would be required to meet the Clive, Utah Waste Acceptance Criteria for our Bulk Waste Facility which is also attached for reference. Please let me know if you need any additional information or have any questions or concerns. Have a great day and remainder of the week.

Attachment: WAC for Bulk Waste Rev 10

From: Kalinina, Elena [mailto:eakalin@sandia.gov]
Sent: Friday, January 14, 2022 12:25 PM
To: Scott Dempsey <sjdempsey@energysolutions.com>
Subject: [EXTERNAL] One More Request

Scott:

I am sorry for multiple requests and thankful for your responses to them. Here is one more.

We are planning to include a short description of Clive in our report. The main reason is to show to the stakeholders why we think that this is an excellent site for disposal. To do that, we need to be able to review the site PA. I wonder if you could provide an access to the PA to us. It also would be helpful to have the state review (Safety Evaluation Report) if possible.

Best regards.

Elena

From: Scott Dempsey <sjdempsey@energysolutions.com>
Sent: Friday, January 14, 2022 10:43 AM
To: Kalinina, Elena <eakalin@sandia.gov>
Subject: RE: [EXTERNAL] One More Request

No worries at all Ms. Elena. Do you mean Performance assessment? If so, I think that is publicly available so might not be an issue. Question for you: Can we review and comment on what you are putting into the report?

From: Kalinina, Elena [mailto:eakalin@sandia.gov]
Sent: Friday, January 14, 2022 12:49 PM
To: Scott Dempsey <sjdempsey@energysolutions.com>
Subject: RE: [EXTERNAL] One More Request

Scott:

Thank you Yes, I meant the performance assessment. I know that there is one from 2000 and that a new one specifically targeting the DU is in the process. I assume that the 2000 one is publicly available? I wonder if you could provide a link to it.

We will appreciate you review and comments.

Elena

From: Scott Dempsey
To: Kalinina, Elena
Subject: RE: [EXTERNAL] One More Request
Date: Monday, January 17, 2022 6:43:05 AM

Good Monday morning Ms. Elena. Please use the following link to gather the information I believe you are looking for. Have a great day and week.

https://deq.utah.gov/waste-management-and-radiation-control/class-a-west-disposal-cellinfiltration-and-transport-modeling-report-energysolutions

From: Kalinina, Elena <eakalin@sandia.gov>
Sent: Thursday, March 10, 2022 4:58 PM
To: Scott Dempsey <sjdempsey@energysolutions.com>
Subject: [EXTERNAL] Write-Up on Clive

Scott:

Attached is the draft section that I wrote on Clive. It is a part of the draft report that will be submitted to DOE on March 15. We will be addressing the DOE comments on the draft report in April. We will generate a final revision of the report by April 14 and will release it to the public.

Please let me know if you have any comments. I can address them in April along with the DOE comments.

Please do not distribute this section to others because it is a pre-decisional draft.

Best regards.

Elena

From: Scott Dempsey
To: Kalinina, Elena
Subject: RE: [EXTERNAL] Write-Up on Clive
Date: Tuesday, March 22, 2022 9:27:13 AM
Attachments: CLIVE PHOTO 2021 11x17.pdf
Appendix G Clive Draft - TO.docx

Good afternoon Elena. I hope you are well. I apologize for my delay in responding. I was on vacation last week and wasn't able to review some of the comments our internal team had made. The attached is a review of the document and then a couple of photos we reference to use. Please let me know if you have any additional questions or concerns.

Have a great day.

From: Kalinina, Elena [mailto:eakalin@sandia.gov]
Sent: Wednesday, February 23, 2022 6:59 PM
To: Scott Dempsey <sjdempsey@energysolutions.com>
Subject: [EXTERNAL] Disposal Cell Question

WARNING: This message is from a non-EnergySolutions sender, please ensure it is from a legitimate source.

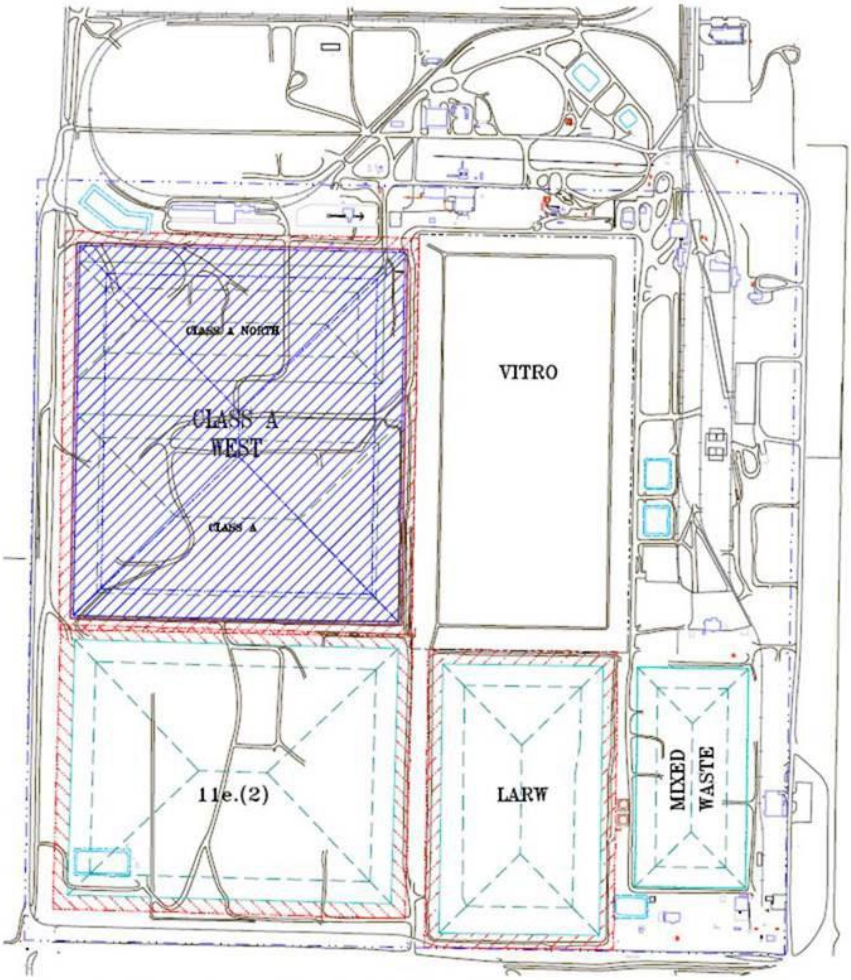
Scott:

Sorry, more questions as I read multiple Clive reports.

I wonder If the Hanford waste would be emplaced in CAW cell.

Also, you mentioned that the facility disposal volume is 3M cub yards. Is this the total of all the cells in the below figure or a particular cell?

Regards.
Elena



From: Scott Dempsey
To: Kalinina, Elena
Subject: RE: [EXTERNAL] Disposal Cell Question
Date: Thursday, February 24, 2022 9:20:12 AM

Good Morning Ms. Elena. Please see the following in regards to your questions:

- Yes we would disposition the Waste in our Class A cell and specifically the "federal disposal cell" of this area.
- Correct, our current capacity is 3M cu yd for the Class A cell.

No worries on additional questions. Just pass them on. Are you or anyone from your group going to the WM Conference in Phoenix?

From: Kalinina, Elena [mailto:eakalin@sandia.gov]
Sent: Monday, February 7, 2022 5:16 PM
To: Scott Dempsey <sjdempsey@energysolutions.com>
Subject: [EXTERNAL] One More Request for Information

Scott:

I appreciate your patience with my questions. I hope to stop bothering you with them soon.

I wonder if you could point me at the information regarding the air permitting at Clive.

Regards.

Elena

From: Scott Dempsey
To: Kalinina, Elena
Subject: Re: [EXTERNAL] One More Request for Information
Date: Thursday, February 10, 2022 6:15:51 AM
Attachments: Air approval 01-25-19.pdf

Good morning Ms Elena. The attached is our air permit. How is the overall evaluation/report coming along. Do you all have a draft completion date yet? I want to make sure we are prepared to review when you all are ready.

---

[1] Dempsey, Scott, 2021, "RE: A Few Questions Related to Disposal," (email to E. Kalinina, December 13, Sandia National Laboratory), Energy*Solutions*, Clive, Utah.

Waste Control Specialists, LLC Responses to FFRDC Questions regarding Regulatory Issues on the Report on Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation

Date; Fri 2/4/2022 2:21 PM
To: Carlson, Dave dcarlson@wcstexas.com
From: Dixon, Paul Robert p_dixon@lanl.gov
Cc: william.bates@srnl.doe.gov
RE: Request for Technical Information on WCS PA

Dave,

It was great talking with you this morning. Attached are 13 questions the FFRDC team would like the WCS licensing team to answer and provide (where possible) a citation reference.

Thank you for your willingness to entertain our questions. If you could have written responses back to me before February 18th that would be greatly appreciated.

Regards,

Paul Dixon
Senior Advisor to NDAA-3125 FFRDC Team

<<<<<<<<<<>>>>>>>>>>
Paul Dixon
Deputy Director
Civilian Nuclear Program Office
Los Alamos, New Mexico 87544
e-mail: p_dixon@lanl.gov
cell: [redacted]
Admin; [redacted]

Attachment:

FFRDC Questions Regarding the WCS Performance Assessment

In the NDAA 2019 report, the FFRDC team made the following statements about conditions at WCS:

A. The Ogallala Formation, if present above the buried red ridge, is not water bearing in the WCS area. However, the Ogallala is saturated to the north and east of the buried red ridge and regionally, the Ogallala Formation is the primary source of groundwater in the Southern High Plains.

B. Because of the low transmissivity and salinity, the 225-foot zone is not classified as a drinking water aquifer.

To support the writing of the supplemental LAW NDAA-3125 report, the FFRDC team would like WCS licensing to provide (where possible) citation references to the following questions:

A) Questions Related to Assumptions Used in the WCS PA:

i) Does the WCS PA for the Federal cell proceed on the assumption that there will be no groundwater contamination coming from the facility during the compliance period?

a) Was the groundwater pathway analyzed and impacts quantified?
b) Was the groundwater pathway not quantified because it was not a viable drinking water source?

ii) What are the reasons why the Ogalala aquifer was excluded from the PA?
a) *A previous study that showed that the red clay layer on which WCS is sitting has been isolated from all the surroundings for the last 500,000 yrs (or more?). Is there a reference for this?*
b) *It has been stated that the zone below the red clay layer can't be consider an aquifer (saline or not) because the wells don't yield any water from this formation. Is this true?*

iii) Is the compliance period 1,000 years or 10,000 years?
iv) Is there a post compliance period?
v) What is the timing of peak impacts
vi) Do you consider mechanisms of contaminate release from the waste forms?
a) If you considered release models, how was this release quantified/modeled?
b) For grouted waste forms, are there degradation and release assumptions?
vii) Is surface water a potential pathway for release of contaminants?
viii) Are air pathway and inadvertent intruder (oil drilling) the main risk drivers and exposure pathways for release of radioactive iodine and technetium (and/or other highly mobile or long-lived contaminants) from the Federal cell?
ix) What are the analyzed points of compliance?
x) What were exposure/dose standards used for each of the key pathways?
xi) For Class B/C wastes going into MCC's, was the MCC long-term performance a factor in the dose/pathway analysis? (i.e., was it key to compliance, or was its performance as a release barrier not considered in the analysis?)

B) <u>Questions Related to the Public Participation and Litigation Process:</u>

i) What was the public participation process followed for licensing the Federal cell at WCS?
ii) Are there any concerns about external stakeholder interference or litigation that might preclude disposal of Hanford Class A, B or C tank waste at WCS?

From: David Carlson <dcarlson@wcstexas.com>
Sent: Friday, February 4, 2022 5:55 PM
To: Dixon, Paul Robert <p_dixon@lanl.gov>
Cc: william.bates@srnl.doe.gov
Subject: [EXTERNAL] Re: Request for Technical Information on WCS PA

Paul

Received your questions. We will start on these on Monday and respond back with any questions that we have.

Kind Regards

Dave

David Carlson
865-201-3191

From: David Carlson <dcarlson@wcstexas.com>
Date: Thursday, Feb 10, 2022, 6:26 PM
To: Dixon, Paul Robert <p_dixon@lanl.gov>
Cc: william.bates@srnl.doe.gov <william.bates@srnl.doe.gov>
Subject: [EXTERNAL] Re: Request for Technical Information on WCS PA

Paul

We have lined up internal staff and subcontractors to prepare responses. While we appreciate the urgency of your request, we estimate that it will be the week of March 7 before we are able to provide fully responsive information.

Thanks for your patience,

Dave

David Carlson
President and COO
Waste Control Specialists, LLC
[redacted]

From: Dixon, Paul Robert <p_dixon@lanl.gov>
Sent: Thursday, February 10, 2022 6:26 PM
To: David Carlson <dcarlson@wcstexas.com>
Cc: william.bates@srnl.doe.gov
Subject: RE: [EXTERNAL] Re: Request for Technical Information on WCS PA

Dave
That sounds perfect!
Thanks again
Paul

Sent with BlackBerry Work
(www.blackberry.com)

From: Renee Murdock <smurdock@wcstexas.com>
Sent: Monday, March 14, 2022 7:16 AM
To: Dixon, Paul Robert <p_dixon@lanl.gov>
Cc: David Carlson <dcarlson@wcstexas.com>
Subject: [EXTERNAL] Responses to the Request for Technical Information on WCS PA

Dear Mr. Dixon:

On behalf of David Carlson, President & COO (WCS), attached are WCS' responses to the request for technical information on the WCS Performance Assessment.

Thank you,

Reneé Murdock, MBA, PMP
Compliance Project Manager
Waste Control Specialists LLC
smurdock@wcstexas.com
Cell: [redacted]

03-14-2022 WCS Responses - FFRDC.p

Date: Mon 3/21/2022 11:28 AM
To: Carlson, Dave dcarlson@wcstexas.com
From: Dixon, Paul Robert p_dixon@lanl.gov
Cc: william.bates@srnl.doe.gov; Tom Brouns (tom.brouns@pnnl.gov)

RE: Additional quests for consideration by the NDAA-3125 team

Dave,
The NDAA-3125 team greatly appreciates the very thorough responses you sent. Having read these responses, several additional questions have be raised that we would like to know if your team could clarify?

1) *The TDS of the 225 zone and the deep zone below the red clays was not given, and we were wondering if that information was sharable.*
2) *What, if any, amendments to the License/RCRA permit might be required in order for WCS to be able to accept substantial quantities of Hanford tank LAW, if the LAW were:*
   a) *liquid tank waste being transported to WCS for stabilization with grout and treatment to meet LDRs, followed by disposal at WCS?*
   b) *grouted tank waste meeting LDRs being transported to WCS for disposal only?*
3) *Does WCS have enforceable agreements with any of its customers that would preclude the return by WCS of mixed waste to the site of origin if upon receipt of the waste at WCS it turns out the waste does not meet WACs or is determined not to meet LDRs (or is unacceptable for treatment or disposal for any other reason)?*
4) *Could WCS lawfully accept Hanford tank LAW for treatment and/or disposal without a WIR determination having been made by DOE that the waste is not HLW?*
5) *Would WCS be prepared to make a "no-migration" petition to EPA if Hanford tank LAW could not meet the LDR requirements?*

Thank you
Paul Dixon
Senior Technical Advisor to the NDAA-3125 Team

From: David Carlson <dcarlson@wcstexas.com>
Sent: Tuesday, March 22, 2022 6:43 AM
To: Dixon, Paul Robert <p_dixon@lanl.gov>
Cc: william.bates@srnl.doe.gov; Tom Brouns (tom.brouns@pnnl.gov) <tom.brouns@pnnl.gov>
Subject: [EXTERNAL] Re: Additional quests for consideration by the NDAA-3125 team

Paul
Here are our responses to your additional questions.

Kind Regards
Dave

1. *The TDS of the 225 zone and the deep zone below the red clays was not given, and we were wondering if that information was sharable.*

   "Groundwater in the Dockum aquifer is generally of poor quality. Water quality ranges from fresh in the outcrop areas to brine in the confined parts of the aquifer. It also tends to deteriorate with depth, and total dissolved solids (TDS) concentrations can exceed 60,000 mg/l in the deepest parts of the aquifer." (Texas Water Development Board - The Groundwater Resources of the Dockum Aquifer in Texas, Bradley and Kalaswad 2003).

   TDS of samples from the 225-foot zone has ranged from 3800 to 4700 mg/L. As noted previously, this zone has very low permeability and cannot produce an adequate quantity of water for consumption.

   By way of reference, water that is above 1200 mg/L is generally considered to be unacceptable for human consumption. The US EPA has established National Secondary Drinking Water Regulations (NSDWRs) that set the secondary maximum contaminant level (SMCL) for TDS at 500 mg/L.

2. *What, if any, amendments to the License/RCRA permit might be required in order for WCS to be able to accept substantial quantities of Hanford tank LAW, if the LAW were:*

   a. *liquid tank waste being transported to WCS for stabilization with grout and treatment to meet LDRs, followed by disposal at WCS?*

      No license amendments or permit modifications are needed for WCS to receive, treat (stabilization/solidification), and dispose of substantial quantities of liquid tank waste that is LLRW or Mixed LLRW.

   b. *grouted tank waste meeting LDRs being transported to WCS for disposal only?*

      No license amendments or permit modifications are needed for WCS to receive and dispose of substantial quantities of grouted tank waste that is LLRW or Mixed LLRW.

3. *Does WCS have enforceable agreements with any of its customers that would preclude the return by WCS of mixed waste to the site of origin if upon receipt of the waste at WCS it turns out the waste does not meet WACs or is determined not to meet LDRs (or is unacceptable for treatment or disposal for any other reason)?*

WCS has enforceable agreements with customers that place the responsibility on the customer to either (a) accept the return of their non-compliant or non-LDR waste or (b) authorize and direct WCS to ship it on behalf of the customer to an authorized third party for additional treatment or storage.

In practice, use of these agreements is extremely unlikely because waste streams are fully characterized prior to shipment to WCS.

4. *Could WCS lawfully accept Hanford tank LAW for treatment and/or disposal without a WIR determination having been made by DOE that the waste is not HLW?*

   Yes, in accordance with License Amendment 38, license condition 142.C; so long as DOE followed an applicable DOE order, policy, or procedure to classify and ship it as LLRW, WCS could still receive, treat, and dispose without a WIR determination.

   > LC 142.C "For the purpose of the Federal Waste Facility, the Licensee is authorized to accept for disposal waste which is handled, treated, packaged, or characterized in accordance with applicable Department of Energy orders, policies, and procedures. Waste class applies when the waste is manifested for transport, regardless if a waste class has been assigned on the manifest documents. The waste class requirements found in 30 TAC 336.362 shall apply."

5. *Would WCS be prepared to make a "no-migration" petition to EPA if Hanford tank LAW could not meet the LDR requirements?*

   No, because under the process that would be used to prepare the waste for shipment to WCS a "no-migration" petition would be unnecessary.

Tue 3/22/2022 10:12 AM
To: Carlson, Dave dcarlson@wcstexas.com
From: Dixon, Paul Robert p_dixon@lanl.gov
Cc: william.bates@srnl.doe.gov; Tom Brouns (tom.brouns@pnnl.gov)

RE: Additional quests for consideration by the NDAA-3125 team

David,

Thank you for the rapid and complete response.

Enjoy the day,
Paul Dixon
Senior Technical Advisor to the NDAA-3125 Team

Wed 3/23/2022 3:32 PM
To: Carlson, Dave dcarlson@wcstexas.com
From: Dixon, Paul Robert p_dixon@lanl.gov
Cc: william.bates@srnl.doe.gov; Tom Brouns (tom.brouns@pnnl.gov)

Dave,

The NDAA team would like to know if the Q&A responses your team provided could be put in an appendix in our report? If you agree, your team will be given the opportunity to review and refine anything that would be part of our public document. Please let me know your decision.

Thank you,
Paul Dixon
Senior Technical Advisor to the NDAA-3125 Team

From: David Carlson <dcarlson@wcstexas.com>
Sent: Wednesday, March 23, 2022 5:34 PM
To: Dixon, Paul Robert <p_dixon@lanl.gov>
Cc: william.bates@srnl.doe.gov; Tom Brouns (tom.brouns@pnnl.gov) <tom.brouns@pnnl.gov>
Subject: [EXTERNAL] Re: Additional quests for consideration by the NDAA-3125 team

Paul

Yes, you are welcome to use them in their entirety in your report. I appreciate the opportunity to review and refine the information that will be in your public document and we will be very pleased to do so.

Kind Regards
Dave

David Carlson
President and COO
Waste Control Specialists, LLC
[redacted]

Appendix L. Relevant Experience in Low Temperature Waste Forms

L.1 INTRODUCTION

Extensive experience exists within the U.S. Department of Energy (DOE) complex with using low temperature immobilization/grout for high volumes of alkaline salt wastes. When coupled with the additional experience with immobilization of other waste types using grouts with DOE and internationally, the technical maturity of the process for waste immobilization is evident, including the potential use of grout as a primary waste form in the alternatives evaluated within this report. This appendix summarizes the existing relevant grout experience across the DOE complex and relevant international examples. Further details on previous campaigns using grouting, including facility decommissioning that is not covered in this appendix are provided in SRNL-STI-2019-00009, *Review of Cementitious Materials Development and Applications that have Supported DOE-EM Missions: Waste Treatment, Conditioning, Containment Structures, Tank Closures, Facility Decommissioning, Environmental Restoration, and Structural Assessments*.

L.2 TEST BED INITIATIVE

The Hanford Test Bed Initiative (TBI) is directly relevant to the grouting alternatives in this study as it involved grouting of treated Hanford tank waste and disposal at an off-site disposal facility. The TBI Phase I and Phase II were developed to show the efficacy of pretreating and processing high-level waste (HLW) supernatant liquid from the Hanford tanks to remove $^{137}Cs/^{90}Sr$, and then grout the resulting low-level waste (LLW) supernatant liquid (alkaline, high salt liquid) prior to off-site disposal at a suitable federal LLW disposal cell such as Waste Control Specialists, LLC (WCS) Federal Waste Disposal Facility in Texas or Clive Disposal Facility in Utah. In addition, the treated and processed waste had to meet both Land Disposal Restrictions (LDR) and Resource Conservation and Recovery Act (RCRA) permitting requirements for off-site disposal. The TBI is directly relevant to the grouting alternatives in this study as the initiate involved grouting of treated Hanford tank waste and disposal at an off-site disposal facility.

L.2.1 Phase I: Waste Incidental to Reprocessing Evaluation – Test Samples of Treated, Low-Activity Waste from Hanford Tanks for Off-site Disposal

TBI Phase I evaluated whether approximately 3 gallons of test samples – consisting of treated, solidified, low-activity waste (LAW) from six Hanford tanks – meet the criteria of waste incidental to reprocessing (WIR) and not radioactive HLW, under Section II.B(2)(a) of DOE M 435.1-1, *Radioactive Waste Management Manual*.

The test sample consisted of low-activity (decanted supernatant liquid) waste from six tanks (Tanks AN-101, AN-106, AP-105, AP-106, AP-107, and AY-101 from the hot cell archive) that contain waste, in part, from the reprocessing of spent nuclear fuel from defense-related activities at the Hanford Site. The composite sample was filtered to remove solids and passed through spherical resorcinol-formaldehyde ion-exchange resin columns to remove cesium in a test bed at the 222-S Laboratory. Following pretreatment at the 222-S Laboratory, the waste was solidified in a grout matrix, to meet RCRA and disposal requirements, at Perma-Fix Northwest Richland, Inc. (RPP-RPT-59874, *Test Report for Cesium and Solids Removal from an 11.5L Composite of Archived Hanford Double Shell Tank Supernate for Off-Site Disposal*). DOE then shipped the treated and solidified waste as LLW to WCS.

This composite sample WIR evaluation demonstrated that the criteria in DOE M 435.1-1, Section II.B(2)(a), could be met. Specifically, the Phase I demonstration (RPP-RPT-59874) showed:

- The treated test samples could be processed to remove key radionuclides to the maximum extent that is technically and economically practical.
- The treated samples meet safety requirements comparable to the U.S. Nuclear Regulatory Commission (NRC) performance objectives for disposal of LLW, set out in 10 CFR 61, "Licensing Requirements for Land Disposal of Radioactive Waste," Subpart C, "Performance Objectives."

- The treated samples were incorporated into a solid physical form at a concentration that did not exceed the applicable concentration limits for Class C LLW, as set out in the NRC regulations at 10 CFR 61.55, "Waste Classification."

This test sample WIR evaluation demonstrated that this treated waste was incidental to reprocessing, was not HLW, and could be managed and disposed of as LLW.

L.2.2 Phase II: Test a New and Innovative Process for Waste Treatment by Performing an In-Tank Pretreatment Process of Filtration and Ion Exchange to Remove Particulates and Cesium-137

TBI Phase II is currently underway and involves pretreating and processing 2,000 gallons of liquid supernatant from Tank SY-101, located in the 200 West Area of the Hanford Site, to remove particulates and $^{137}Cs/^{90}Sr$, then grouting the remaining liquid for off-site disposition at WCS. For TBI Phase II, DOE is currently only publicly communicating the ongoing WIR process (DOE-ORP-2021-01, *Draft Waste Incidental to Reprocessing Evaluation for the Test Bed Initiative Demonstration*; Colborn, 2022). The project will hold public meeting per the dates cited in the Draft WIR. The project is on-track for meeting the follow-on regulatory activities related to National Environmental Policy Act (NEPA) and RCRA permitting. The current target schedule shows that the project will be ready for fieldwork activities beginning in fiscal year (FY) 2023.

L.3 SAVANNAH RIVER SITE SOLIDIFICATION AND DISPOSAL

Previous and on-going grouting activities at the Savannah River Site are directly relevant to Hanford as a high volume of alkaline salt waste is being immobilized in grout, the composition of this liquid waste is very similar to the projected blended Hanford supplemental LAW feed vector (see Volume II, Appendix A, Section A.3.2), and a vault disposal is being used similar to alternatives Grout 5A and 5B.

L.3.1 Saltstone

The Savannah River Site (SRS), Hanford Site processed reactor fuel-target assemblages to recover isotopes for defense needs. Raffinates (liquid portion remaining after solvent extraction) generated by the isotope separation processes were accumulated and stored at the site. SRS operated the plutonium-uranium extraction (PUREX) process (with both highly enriched uranium and depleted uranium, which produced very different waste streams). In the waste treatment mission at SRS, grout has been used extensively to date.

The SRS Saltstone Facility began operation in 1991 to stabilize the decontaminated aqueous salt fraction in a hydrated cementitious matrix. Salt solution and reconstituted salt cake are removed from the HLW tanks, decontaminated with respect to cesium, strontium, and actinides, and the resulting 5-6 M Na salt solution is transferred to the Saltstone Production Facility where it is mixed with preblended cement, slag, and fly ash. To date, over 17 Mgal of saltstone have been produced and disposed of in engineered containment structures called Saltstone Disposal Units (SDU) (Figure L-1).

Figure L-1. Aerial View of Saltstone Disposal Units at Savannah River Site

The nominal composition of decontaminated low-activity salt solution that is processed in the Saltstone Facility is shown in Table L-1.

Table L-1. Savannah River Site Salt Solution Composition

Nominal Composition		Radioactive Contaminants (nominal)		
Chemical	mol/L	Isotope	Bq/mL	Half-Life (yr)
Na^+	6	^{90}Sr	74	28.8
NO_3^-	3	^{99}Tc	740	0.2M
OH^-	2	^{129}I	37	16M
NO_2^-	0.5	^{137}Cs	37,000	30.2
CO_3^{2-}	0.2			
SO_4^{2-}	0.1			
pH	> 13			
sp.gr.	≈ 1.23			

While the Saltstone formulation is commonly considered as a set ratio, the same blend of reagents has not been used for all campaigns to date and a permitted range is the actual control (Table L-2). A summary of salt processing campaigns at SRS to date are shown in Table L-3.

Table L-2. Saltstone Waste Form Composition

Ingredient	Cement Reagent Blend[a] wt%	SCDHEC Permitted wt% range
Portland Cement, Type I/II	10	0 – 10
Blast Furnace Slag	45	20 – 60
Class F Fly Ash	45	20 – 60
Salt Solution	48	--
Water/Cementitious Materials: 0.58 – 0.6		

[a] The same blend has been used for all campaigns to date.
SCDHEC = South Carolina Department of Health and Environmental Control.

Table L-3. Savannah River Site Saltstone Processing Campaigns

Waste Description	Date of Operation and Waste Volume	Cementitious Waste Form Matrix
In-Tank Precipitation Demonstration Waste Campaign Waste water generated during demonstration of sludge washing and removal of Cs, Sr, and actinides from salt solution (tetra phenyl borate, sodium titanate precipitation). Concentrated salt solution was variable and contained 3-6 M (~32 wt%) dissolved Na salts ($NaNO_3$, $NaNO_2$, Na_2SO_4, $NaAl(OH)_4$, carbonate, oxalate, phosphate, and NaOH with pH ≥ 14). No further processing once benzene was detected in the process.	1991–1992 ~600,000 gal	Saltstone cement-based waste form **Portland Cement I/II** — **10 wt%** Blast Furnace Slag — 45 wt% Class F Fly Ash — 45 wt% Salt Solution — 48 wt% Water/Cementitious Materials: 0.58-0.6
Deliquification, Dissolution, and Adjustment Campaign (No Cs, Sr, actinide removal post retrieval from tanks). Tank 41 dissolved salt solution that has been deliquefied (i.e., extracting the interstitial liquid), dissolved by adding water and pumping out the salt solution, and adjusted for processing at SPF in Tank 41.	2007–2009 2.8 Mgal < 0–5 MCi 600,000 Ci limit including ARP/MCU	Saltstone Same as above

Table L-3. Savannah River Site Saltstone Processing Campaigns

Waste Description	Date of Operation and Waste Volume	Cementitious Waste Form Matrix
ARP/MCU Decontaminated Tank Salt Waste Campaign Decontaminated 3–6 M Na salt supernatant resulting from spent nuclear fuel reprocessing for defense purposes commingled with other types of wastes from weapon production and space mission. Waste decontamination method: **ARP** – ^{90}Sr and actinide removal with MST and filtration **MCU** – Cs removal with modular CSSX unit	2008–2017 7–8 Mgal 600,000 Ci limit – including deliquification, dissolution, and adjustment	Saltstone Same as above
SWPF Decontaminated Tank Salt Waste Campaign SWPF will incorporate both the ARP and CSSX processes in a full-scale shielded facility capable of handling salt with high levels of radioactivity.	Future Start (TBD) 200,000 Ci limit	Contemporary Saltstone composition range. Saltstone uses an operational range of 20 wt% - 60 wt% BFS (now slag cement), 20 wt% - 60 wt% FA (now thermally-beneficiated Class F FA) and 0 wt% - 10 wt% OPC.

ARP	=	actinide removal process.	MST	=	monosodium titanate.
BFS	=	blast furnace slag.	OPC	=	ordinary portland cement.
CSSX	=	caustic-side solvent extraction.	SPF	=	Saltstone Production Facility.
FA	=	fly ash.	SWPF	=	Salt Waste Processing Facility.
MCU	=	modular caustic-side solvent extraction unit.	TBD	=	to be determined.

L.3.2 Other Savannah River Site Solidification and Disposal

Other campaigns at SRS have used immobilized low-level solid and mixed wastes and are discussed in the following subsections.

L.3.2.1 Savannah River Site – Ashcrete from the Consolidated Incineration Facility

The Consolidated Incineration Facility (CIF) at SRS was designed to treat low-level radioactive, hazardous, and mixed wastes in both solid and liquid forms (ERD-EN-2009-0101, *Scoping Summary for the Consolidated Incineration Facility*). Construction of the CIF began in November 1992 and operations were conducted from 1997 to November 2000. During operation, the CIF generated two residual waste streams: ash formed as a combustion product in the rotary kiln, and blowdown liquids from the recirculation of scrubbing and cooling water in the offgas clean-up system. These two waste streams (ashcrete – made from ash; blowcrete – made from blowdown) were stabilized via the ashcrete process at CIF by encapsulation in a cement matrix to form a solid monolithic structure in 55-gal drums (ash was mixed with cement [dry or wet] in drums, and the drums were tumble-mixed; time to set was typically 28 days) (Simpson and Charlesworth, 1989; HLW-99-0008, *High Level Waste System Plan*; Roberson, 1982). The containerized/solidified ashcrete and special case blowcrete forms were buried in shallow unlined trenches in E-Area at SRS (WSRC-TR-99-00239, *Permeability of Consolidated Incinerator Facility Wastes Stabilized with Portland Cement*).

L.3.2.2 Savannah River Site – Naval Fuels

The 247-F Fuel Manufacturing Facility (FMF) operated from 1985–1989. This facility was to convert uranium stock into a form suitable for naval fuel. The facility was deemed redundant to other naval fuel pilot plant facilities and shutdown in 1989. Low-level liquid waste from the startup and brief operation of the FMF was converted into "saltcrete." In 1987, a recommendation was made to change from a cement-only to a cement-fly ash saltcrete mixture (Harley and Langton, 1987). The change would eliminate the excessive heat buildup (>100°C) experienced with the cement-only formulation and improve the waste form (less contaminant release) and lower costs. In total, more than 6,500 drums of saltcrete – waste generated from FMF operations and shutdown – were disposed of in the Z-Area Vaults (Odum, 1990).

L.4 FEDERAL DISPOSAL FACILITIES GROUT CAPABILITIES AND EXPERIENCE

Off-site disposal of a primary LAW waste form is considered in several alternatives in this study, and as such, experience and capabilities at federal disposal facilities is directly relevant. These federal disposal facilities take liquid waste and apply specific treatments at their location, then dispose of the resulting waste form. The specific treatments used at these facilities are not committed to a single formulation or process; instead, the treatment is dictated by the characteristics of the waste and the needs of the final waste form for disposal at their facility.

L.4.1 Waste Control Specialists, LLC Federal Waste Disposal Facility

The Texas Storage and Processing Facility (TSDF) at the WCS Federal Waste Disposal Facility has capabilities to treat and solidify liquid low-level radioactive waste for disposal from commercial, state, and federal facilities. An example of this treatment process is the approximately 16,000 gal/month of liquid radioactive waste from Vermont Yankee Nuclear Power Plant (two tankers/month) that WCS has been solidifying for on-site disposal. WCS formulates the solidification ingredients based on waste characteristics and classification. WCS accepts both DOE and U.S. Department of Defense (DoD) waste for treatment and/or disposal in their Federal Waste Disposal Cell (WCS, 2017).

L.4.2 Clive Disposal Facility

The Energy*Solutions* disposal facility in Clive, Utah is permitted, licensed, and authorized to receive, treat, and dispose of Class A low-level radioactive waste, naturally occurring and accelerator-produced radioactive material (NORM/NARM), and Class A mixed low-level radioactive waste. Waste shipped to Energy*Solutions* for treatment or liquid solidification/verification prior to disposal is managed at the Energy*Solutions* treatment facility. The treatment facility is designed for radioactive waste that requires treatment for RCRA constituents and for liquid radioactive wastes requiring solidification prior to disposal. Mixed waste treatment and solidification capabilities include (BWF WAC, 2015):

- **Chemical stabilization** – Including oxidation, reduction, neutralization, and deactivation.
- **Amalgamation** – For the treatment of elemental mercury.
- **Macroencapsulation in grout** – For the treatment of radioactive lead solids, RCRA metal-containing batteries, and hazardous debris.
- **Liquid solidification in tailored grouts** – For the solidification of radioactively contaminated liquids (e.g., aqueous solutions, oils, antifreeze) to facilitate land disposal. Mixed waste liquids can also be treated and solidified at the treatment facility.
- **Vacuum thermal desorption (VTD) of organic constituents** – For the thermal segregation of organic constituents from wastes, including wastes with polychlorinated biphenyl (PCB). Waste containing PCB liquids is also acceptable for VTD treatment. Liquids will require solidification prior to processing through the system. The organic liquid condensate generated in the VTD process must be treated prior to final disposal. The non-liquid waste residue will be further treated for metal contaminants (if required) and disposed at the mixed waste embankment.
- **Debris spray washing** – To remove contaminants from applicable hazardous debris.

L.5 HANFORD HISTORY WITH GROUT

The Hanford site also has relevant history in the use of grout for waste immobilization and stabilization. This section provides an overview of these grout activities and also summarizes the history of grout development for Hanford LAW.

L.5.1 Hanford Grout Vaults

The initial immobilization plan for liquid wastes at Hanford was grouting and subsequent disposal in large vaults located in the Hanford 200 East Area. In 1987, the Grout Treatment Facility was constructed at Hanford, and beginning in 1988, more than 1.4 Mgal of phosphate sulfate waste from decontamination and basin management programs at the Hanford N Reactor were immobilized in a grout vault (Huang et al., 1994). The Grout Treatment Facility was planned to immobilize the phosphate sulfate waste, cladding removal wastes, and double-shell tank (DST) supernatant liquid (termed double-shell slurry feed [DSSF]) (Serne et al., 1992). For each of these wastes, a different formulation was selected. The phosphate-sulfate waste and cladding removal waste formulations were developed at Oak Ridge National Laboratory (ORNL) and were based on that laboratory's hydrofracture grouting program; however, this formulation was designed for environmental injection where water sorption occurs, not a vault design (Sams et al., 1988). The DSSF formulation more closely replicated the saltstone formulation being developed in parallel at SRS. A 1.5 Mgal demonstration vault was poured using phosphate-sulfate wastes from Hanford N Reactor decommissioning activities (PNL-8067, *Characterization of a Low-Level Radioactive Waste Grout: Sampling and Test Results*). Several vaults to receive the first DSSF grout were constructed but not filled, following a revision to the Tri-Party Agreement (TPA) (Ecology et al., 1989) defining glass as the baseline immobilization technology for LAW in 1993. Little grout work at Hanford occurred between 1995 and 2001.

L.5.2 Hanford Grout Development for Low-Activity Waste

This section describes the development of grout technology for Hanford LAW; a description of the TBI activities is provided in Section L.2. In 2002, a cleanup mission acceleration plan was proposed and included evaluations of supplemental technologies to support vitrification at the Hanford Waste Treatment and Immobilization Plant (WTP) (PNNL-14280, *Preliminary Assessment of Supplemental Grout and Glass Wasteforms for Disposal of Low-Activity Waste*). A containerized grout, termed containerized Cast Stone, was evaluated as part of this effort to provide data for a LAW supplemental treatment risk assessment (RPP-17675, *Risk Assessment Supporting the Decision on the Initial Selection of Supplemental ILAW Technologies*). The current baseline formulation for Cast Stone was defined in RPP-RPT-26743, *Hanford Containerized Cast Stone Facility Task 1-Process Testing and Development Final Report*. The Cast Stone formulation was chosen from a set of four formulations (RPP-RPT-26743), which were based on grout vault era programs.

Following the supplemental LAW risk assessment (RPP-17675), little to no development of grout for LAW was performed at Hanford. Instead, research focused on providing qualification data for liquid secondary waste grout where Cast Stone was again identified as the baseline formulation (PNNL-25129, *Liquid Secondary Waste Grout Formulation and Waste Form Qualification*; PNNL-19122, *Review of Potential Candidate Stabilization Technologies for Liquid and Solid Secondary Waste Streams*). Grout is the baseline immobilization approach to be used for liquid and solid secondary wastes generated at WTP.

Recent reports are available to summarize the development of secondary waste grout, including:

- PNNL-25129, *Liquid Secondary Waste Grout Formulation and Waste Form Qualification*
- PNNL-26443, *Updated Liquid Secondary Waste Grout Formulation and Preliminary Waste Form Qualification*
- PNNL-28545, *Development and Characterization of Cementitious Waste Forms for Immobilization of Granular Activated Carbon, Silver Mordenite, and HEPA Filter Media Solid Secondary Waste*
- PNNL-28917, *Leach Testing of Laboratory-Scale Melter Evaporator Condensate Cementitious Waste Forms*

- PNNL-32458, *Evaluation of Degradation Mechanisms for Solid Secondary Waste Grout Waste Forms*
- SRNL-STI-2018-00342, *Stabilization of Spherical Resorcinol Resin in Grout- Maintenance of the Hanford Integrated Disposal Performance Assessment FY 2018*
- SRNL-STI-2020-00563, *Ultra-High-Performance Concrete for Encapsulation of HEPA Filters*
- VSL-19R4630-1, *Formulation Development and Testing of Ammonia Tolerant Grout*
- VSL-20R4800-1, *Maturation of Grout Formulation and Immobilization Technology for Effluent Treatment Facility High-Ammonia Waste*
- VSL-21R4950-1, *Maturation of Grout Formulation and Immobilization Technology for Effluent Treatment Facility High-Ammonia Waste*.

Over the last 10 years, Washington River Protection Solutions, LLC (WRPS) has supported a LAW Supplemental Treatment Technology Development Program, with assistance from the Pacific Northwest National Laboratory (PNNL), Savannah River National Laboratory (SRNL) and Vitreous State Laboratory (VSL) at The Catholic University of America, to obtain information on candidate cementitious waste forms for LAW treatment. Cast Stone, a formulation comprising 47 wt% ground granulated blast furnace slag Grade 100, 45 wt% Class F fly ash, and 8 wt% ordinary Portland cement (OPC) Type I/II, has been considered the baseline cementitious waste forms formulation for LAW based on a down-selection in 2005. Beginning in FY 2013, a screening of cementitious waste form formulation parameters (sources of dry materials and mix ratios of waste [free water) to dry blend) and LAW composition was performed to understand their impact on the processing and final Cast Stone waste form properties (PNNL-22747, *Supplemental Immobilization of Hanford Low-Activity Waste: Cast Stone Screening Tests*). The screening effort showed Cast Stone to be a robust waste form based on the measured mechanical and leaching properties that met disposal acceptance criteria for the Integrated Disposal Facility (IDF), despite variations in LAW composition. In FY 2014, the first engineering-scale demonstration of Cast Stone for LAW immobilization was successfully conducted using a pilot-scale facility at SRNL (SRNL-STI-2014-00428, *Engineering Scale Demonstration of a Prospective Cast Stone Process*).

In 2016, the impact of iodine loading and different technetium species on Cast Stone leaching behavior over standard and extended leach durations was evaluated (PNNL-24297, *Extended Leach Testing of Simulated LAW Cast Stone Monoliths*). The study showed that iodine loading (below 0.14 wt%) had little influence on iodine release, whereas the amount of technetium released from the cementitious waste forms is dependent on speciation, where the Tc(I)-tricarbonyl gluconate species leached more than pertechnetate ($TcO4^-$). The study also showed that the observed diffusivity values for Tc and I were constant for upwards of 1,000 days of leaching and that observed diffusivities were consistently lower when the leachant used as a simulated Hanford groundwater compared with deionized water. Characterization of the long-term leach samples were performed in FY 2016 and found that beneficial aging processes are possible, and the waste forms had minimal chemical change (PNNL-25578, *Solid State Characterizations of Long Term Leached Cast Stone Monoliths*). Research was also directed toward improving the retention of technetium and iodine within Cast Stone through the use of getter materials. Two efforts screened candidate technetium and iodine getters using batch tests, focusing on getter materials developed in the laboratory (PNNL-23282, *Technetium and Iodine Getters to Improve Cast Stone Performance*; PNNL-23667, *Evaluation of Technetium Getters to Improve the Performance of Cast Stone*). The two best getters for technetium capture in LAW (Sn(II)-apatite and KMS-2) and the two best for iodine capture in LAW (Ag-zeolite and argentite/Ag2S) were then selected for testing in Cast Stone (PNNL-25577, *Getter Incorporation into Cast Stone and Solid State Characterizations*).

This study showed that KMS-2 was successful at improving technetium retention in vadose zone pore water at only <0.1 wt% added to the waste form; the Sn(II) apatite was minimally effective, while the iodine getters added at 100× an equimolar amount (~0.1 wt%) were not effective.

A concurrent study was performed at SRNL to study Cast Stone using an SRS Tank 50 sample that was chemically adjusted to better match Hanford LAW (SRNL-STI-2016-00619, *Analysis of Hanford Cast Stone Supplemental LAW using Composition Adjusted SRS Tank 50 Salt Solution*). The most important finding of this work was that the addition of 5 wt% of Ag-zeolite as an iodine getter significantly improved iodine retention.

In FY 2019, PNNL performed a modeling effort using IDF waste form simulations to assess the required performance of an inventory of grouted LAW in the IDF (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*). The simulations assumed a constant performance with time and the current inventory of supplemental LAW. The assessment highlighted where further developments in waste form performance are required, including improved retention of contaminants of primary concern (iodine and technetium) in cementitious waste forms. The study provided performance metrics against which laboratory leach data can be assessed. As a follow-on study, an expert panel was assembled to evaluate and present technologies to improve the performance of a grouted LAW inventory through waste form adjustment, pretreatment, and disposal options (SRNL-STI-2020-00228, *Evaluation of Technologies for Enhancing Grout for Immobilizing Hanford Supplemental Low-Activity Waste (SLAW)*). One such technology that was highlighted was the use of additional getters for technetium and iodine capture and immobilization – beyond the materials already tested. In FY 2021, VSL tested a series of geopolymer waste form formulations for immobilization of LAW that in some cases included the use of getter materials. The leach performance of the geopolymers was promising; however, a performance evaluation of an Ag-zeolite iodine getter was misled by the amount of getter added and an unrealistically high iodine concentration.

L.5.3 Other Hanford Solidification and Disposal

Grouting has also been used at Hanford for the stabilization of solid LLW and mixed debris. The fundamental objective of the Environmental Restoration Disposal Facility (ERDF) (regulated by the U.S. Environmental Protection Agency [EPA] under the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* [CERCLA]) is to support the timely removal and disposal of contaminants from various locations within the Hanford Site (EPA/ROD/R10-95/100; Benson et al., 2007). Under RCRA and the Washington Administrative Code (WAC) LDR treatment requirements, waste that meets the definition of debris can be treated using macroencapsulation. ERDF accepts waste that is categorized as long, large, and/or heavy hazardous (LLHH).

The macroencapsulation method to be used for treatment of the LLHH waste items is performed in an ERDF trench by flood grouting (DOE and EPA 2015). LLHH waste items to be macroencapsulated are brought to ERDF from the waste site, driven into the disposal trench, and directly placed on concrete blocks, pads, or inorganic standoffs to elevate the waste debris above the ground, allowing the free flow of grout to completely surround and cover the waste items (all voids and cavities present in the waste debris are also filled). The macroencapsulated (flood-grouted) LLHH waste debris is cured for at least 1 week before the debris is covered with soil. LDR treatment with grout in this manner satisfies 40 CFR 268.45, “Treatment Standards for Hazardous Debris.”

L.6 WEST VALLEY DEMONSTRATION PROJECT

The cleanup mission at the West Valley Demonstration Project (WVDP) is directly relevant to this study as alkaline salt waste from the PUREX process was solidified using grout, transported over a long distance, and disposed of at off-site facilities. This section covers the history of those activities and other closure activities at WVDP using grout.

L.6.1 West Valley Demonstration Project Grouting of Liquid Low-Level Waste

Grouting has been employed previously at the WVDP. Prior to processing, two tanks contained approximately 600,000 gallons of HLW. The primary HLW waste streams were (1) basic plutonium-uranium extraction (PUREX) waste consisting of a precipitated sludge and supernatant liquid, and (2) 15,000 gallons of thorium extraction (THOREX) waste that was combined with spent ion-exchange resins from processing of the PUREX waste. Processing of these wastes generated streams that were immobilized as LLW for disposal.

L.6.1.1 Decontaminated Supernatant Liquid from Tank 8D-2 and Washed Soluble Salts from High-Level Waste Sludge

The supernatant liquid fraction of the PUREX waste was decanted, pretreated, and solidified as LLW to reduce the HLW volume, and further reduced by washing the soluble salts from the sludge, which was also solidified as LLW. These pretreatment processes were performed using the Supernatant Treatment System that used different zeolite media-filled ion-exchange columns to remove soluble cesium (^{137}Cs), strontium (Sr) and plutonium (Pu). These constituents were retained on the zeolite media and that was then solidified as HLW through vitrification.

An on-site Cement Solidification System was used to process the approximately 800,000 gallons of decontaminated HLW supernatant liquid and sludge wash concentrate (20 to 40 wt% total dissolved solids [TDS]) into 19,877 71-gal square drums. In June 2005, DOE published its final decision on the WVDP Waste Management Environmental Impact Statement (EIS) (DOE/EIS-0337F, *West Valley Demonstration Project Waste Management Environmental Impact Statement, Final*). In this EIS, DOE implemented the preferred alternative for the management of LLW and mixed LLW. Using a waste determination process (WVDP, 2006) approved in the final WVDP EIS, LLW was solidified and shipped to the Nevada Test Site in 2006 and 2007. Waste forms met concentration limits for and were disposed as Class C LLW. Both the decontaminated supernatant and the sludge wash liquid were solidified using a formulation comprising Portland Type I cement with $Ca(NO_3)_2$ (to facilitate early gelation to allow timely transport of drums to a storage area), Antifoam (GE AF-9020), and sodium silicate.

Note that WVDP switched to Portland Type 5 cement around July 1994 to limit production of ettringite within the waste form and improve performance during the cement waste core immersion testing. The Type 5 cement worked better (i.e., much less cracking of the cores during immersion testing and higher core compressive strengths), highlighting the ability of grout waste forms to be tailored/improved as a treatment mission evolves.

L.6.1.2 Decontaminated Sodium-Bearing Wastewater

Several processing steps within the WVDP flowsheet generated sodium-bearing wastewater (SBWW), including using pressurized clean water to lubricate and cool drive line bearings in the pumps and to mobilize the sludge and zeolite solids. In addition, the Supernatant Treatment System used an evaporator to reduce liquid volume, with the evaporator bottoms cycled back to the tank system. As part of tank corrosion control, sodium salts were added to the carbon steel HLW tanks and to the extent possible, the dissolved sodium was kept separately from wastes fed to the WVDP Vitrification Facility. The resultant liquid was the SBWW stream, which was later grouted after a WIR was completed (WVDP, 2007).

The SBWW was immobilized as a grout, with the primary target being to stabilize the chromium to pass the Toxicity Characteristic Leaching Protocol (TCLP) test. The formulation used included sodium hydrosulfide (NaHS) (to reduce and precipitate the Cr), granulated ground blast furnace slag, undensified silica fume, and Type 1 Portland cement. Using a waste determination process (WVDP, 2007) approved in the final WVDP EIS (DOE/EIS-0337F), the sodium-bearing wastewater solutions were solidified and shipped to the Nevada Test Site for disposal in 2007. Waste forms met concentration limits for and were disposed as Class B LLW.

The solidified ≈20,000 71-gal square drums of solidified decontaminated supernatant liquid and sludge wash, plus some 55-gal drums containing solidified flush liquid/solids and 17, 170-ft^3 IP-2 containers with SBWW were shipped to the Nevada Test Site for disposal as LLW.

When continued waste retrieval and delivery to the WVDP Vitrification Facility were not appreciably removing additional radioactivity, a determination was made that the criterion of removing key radionuclides from the tanks to the maximum extent technically and economically practical had been reached (Case, 2001). At that point, waste retrieval and vitrification operations were concluded in September 2002 (Williams, 2002).

L.6.2 Other West Valley Demonstration Project Grouting Activities

Grouting was also used in the solidification, encapsulation, and stabilization of several other wastes at WVDP. A summary of those activities is provided in the following subsections.

L.6.2.1 West Valley Demonstration Project High-Level Waste Vitrification Melter, Concentrator Feed Make-up Tank, and Melter Feed Hold Tank Grouting to Meet Waste Incidental to Reprocessing

Lightweight cellular concrete (LCC, Cell-Crete Corporation) was used to grout inside the spent melter and between the melter and its carbon steel container. LCC was made up of a mixture of Type I/II Portland cement and washed concrete sand, with a foam introduced to get to a 31 vol% air mixture. The WIR evaluation defined the encapsulated melter as Class C LLW (WVDP, 2012). In addition, two additional vitrification system components: (1) concentrator feed make-up tank, and (2) melter feed hold tank were grouted in custom-shielded carbon steel boxes similar to how the melter was grouted and met Class C LLW (WVDP, 2013). In 2018, MHF Services transported the grouted, containerized, vitrification melter, concentrator feed make-up tank, and melter feed hold tank steel packages by heavy haul truck from West Valley to a rail yard in Blasdell, New York. From there, all three packages were loaded onto a rail car and shipped for disposal at WCS.

L.6.2.2 West Valley Demonstration Project Grouting of Large Underground Cell

WVDP grouted a large underground cell (46 ft long, 11 ft wide, and close to 20 ft tall), approximately 30 ft below ground, used for spent fuel reprocessing operations to provide structural stability for heavy demolition equipment to be used to tear down the Main Plant Process Building. Before grouting, all major process equipment was removed, interior surfaces decontaminated and sealed, utilities disconnected, and characterization of interior surface debris to facilitate future waste disposal was completed.

L.6.2.3 West Valley Demonstration Project Underground Storage Tanks

Closure of the former HLW storage tanks is still awaiting an EIS and DOE record of decision (ROD). The proposed concept would be to place low-density grout in most of the tank and tank vault annulus, with a higher strength grout on top as an intruder barrier. The lower density grout would help limit long-term sinking of the tank structure in the soil. No WIR yet exists for the tank waste.

L.7 SEPARATIONS PROCESS RESEARCH UNIT

The cleanup mission at the Separations Process Research Unit (SPRU) is directly relevant to this study as alkaline salt waste from both the reduction-oxidation (REDOX) and PUREX processes were solidified using grout, transported over a long distance, and disposed of at off-site facilities.

SPRU, in New York state, was operated from 1950 to 1953 to test the REDOX and PUREX processes to support operations at Hanford and SRS. At the end of operations, sludge waste was present in seven underground tanks, and 9,700 gallons of waste were combined in 2010 for processing. The radionuclide content of the sludge was ~87% from ^{137}Cs and ^{90}Sr, with the remainder from transuranic radionuclides. The waste also contained mercury, lead, chromium, and was characterized as a RCRA hazardous waste. The immobilization process involved mixing the contents of the storage tank for 2 hours, with an aliquot moved to a "day tank" where dose readings were taken and a sample analyzed. If the sample radionuclide concentrations (based on the stabilized waste form concentration) met the waste acceptance criteria, the batch of waste was transferred to a solidification liner for immobilization. A formulation of OPC/fly ash/blast furnace slag was mixed with the batch using a sacrificial paddle within the liner. Once the waste form was set and no free liquids were present, the liner was moved to a shielded storage area before shipping. In all, 28 waste forms were shipped to WCS in Texas for disposal between September 2013 and February 2014 (Hurley and Tonkay, 2016).

L.8 OAK RIDGE RESERVATION

The cleanup mission at the Oak Ridge Reservation is directly relevant to this study as alkaline salt waste from reprocessing were solidified using grout – the main difference being the resulting grout was injected into hydrofractured shale.

The X-10 site at the Oak Ridge Reservation started development in the late 1940s as a pilot plant for plutonium production and separation, then became a non-weapons chemical separations process for nuclear products and radioisotopes (SAND2006-6506C, "Historical Review of Oak Ridge National Laboratory Grout Injection Program"). The resulting wastes from this process were disposed of in Melton Valley, Tennessee, in shallow unlined trenches and auger holes. These processes resulted in groundwater contamination and to stabilize the wastes, grout injections were used between the 1950s and the 1980s. The grout used consisted of 42 wt% Type I Portland cement, 34 wt% Class F fly ash (which helps in strontium retention), 16% attapulgite clay for water absorption, 8 wt% Indian red potter clay (aids in cesium retention), along with liquid wastes from X-10. The X-10 liquids were alkaline and contained nitrate, carbonate, and sulphate. Results from an experimental grout injection site after 2 years emplacement, which were analyzed 20 years later, showed that radionuclides had not migrated into the host shale. The shale fracture grouting performed served as the basis for much of the original grout work at SRS and Hanford even though the grout was designed for environmental injection, not containerization.

L.9 LOS ALAMOS NATIONAL LABORATORY

At Los Alamos National Laboratory (LANL), three types of liquid radioactive waste have been stabilized in cemented waste forms. These campaigns are relevant to potential grouting activities at Hanford as some of the Hanford waste inventory may be classified as transuranic (TRU) waste, similar to the LANL effort.

L.9.1 Radioactive Liquid Waste from TA-50

Radioactive liquid waste is transferred to the Radioactive Liquid Waste Treatment Facility (RLWTF) from multiple generators within the plutonium facility at TA-55. The TRU-bearing radioactive liquid waste influent is treated with ferric sulfate, where the majority of radionuclides are precipitated into a sludge. A 55-gal drum is prepared with 3 gal of zeolite and approximately 270 lb of Type 2 Portland cement. 2.5 gallons of 40% sodium silicate is added to the drum, after which 22 gallons of sludge is introduced to the prepared drum. The drum is tumbled end-over-end to ensure complete mixing, then staged, and given sufficient time to cure. The drums are then shipped to the Waste Isolation Pilot Plant (WIPP) for disposal as contact-handled TRU waste (PA-RPT-01069, *Process Acceptable Knowledge Report for RLWTF Operations*).

L.9.2 Cement Fixation of Transuranic Waste from TA-55

Cement fixation has been used at LANL since 1980. The process converts TRU waste to a form that meets both the WIPP criteria for waste acceptance and the RCRA definition of nonhazardous waste. The primary wastes treated with cement fixation are generated by nitric acid-based processes. These waste streams are first sent to an evaporator that separates them into distillates and bottoms fractions. The bottoms and unrecyclable low-acid distillates are solidified via cementation. Other wastes suitable for cementation include particulates from throughout TA-55, items from the vault, sweepings, waste solutions, and analytical sample returns.

Pretreatment and cementation of the wastes are performed in 55-gal drums inside a glovebox system. Distillate from the evaporator or industrial water are used to dilute acid wastes to prevent their constituents from interfering with the cementation reaction. The diluted wastes are pH adjusted in the drum with sodium hydroxide to make them compatible with Portland cement.

Particulates are added to the drum before the acid waste. Cement powder is delivered from a bulk silo to the drum and mixed with the pH-adjusted waste liquid. The in-drum cementation system minimizes the number of personnel required to operate the process and the time required to produce a drum of cemented waste. The system can process up to four drums a week with two operators (ARQ, 2008).

L.10 EXAMPLES OF INTERNATIONAL GROUT USE

Conditioning of radioactive waste is defined internationally as those operations that transform radioactive waste into a suitable form (i.e., a waste package) for handling, transport, storage, and/or disposal. Globally, conditioning often includes immobilization of radionuclides, containerization of the waste, and additional packaging (overpacking) (IAEA, 2018), and immobilization processes include solidification, embedding, or encapsulation to reduce potential for migration or dispersion of the radionuclides. A summary of conditioning technologies used around the world for a wide range of radioactive waste types is provided in Table L-4.

Table L-4. Summary of Waste Types and Applicable Conditioning Technologies

	Ambient or Low Temperature Thermal Technologies													Thermal Technologies								
	Solidification/ Encapsulation						Solidification		Encapsulation													
	Cementation						Sorbents		Polymers			De-watering		Stabilization				Melting		Vitrification		
																		Metal Matrix		Glass Matrix		
Waste Type	Portland cement (PC) and blended PC	Calcium aluminate cement	Calcium sulpho-aluminate cement	Phosphate cement	Geopolymers	Sorption - Cementation	Inorganic (clays)	Super-absorbent polymers	Thermo-plastics	Thermo-set	Bitumen	Drying / Crystallization	Calcining	Pyrolysis/Steam Reforming	Ceramics and Glass-ceramics	Hot isotactic pressing	Annealing	Powder binders	Metals / Alloys	Silicate glass	Phosphate glass	Containerization
Liquids																						
Aqueous liquids	M	M	D	M	M	M	M	M	-	M	M	M	M	D	M	-	-	-	-	M	L	-
Sludges & precipitates	M	D	D	M	M	M	M	M	L	D	M	M	M	D	D	M	-	-	-	M	L	-
Wet solids (IX resins)	M	D	D	L	D	D	-	-	M	M	M	M	M	M	L	M	-	-	-	D	L	-
Organic liquids, sludges	M	-	L	L	M	M	M	M	L	M	-	-	-	D	-	-	-	-	-	-	L	-
Aqueous-organic liquids & sludges	M	-	-	D	M	M	M	M	L	-	-	M	-	D	-	-	-	-	-	D	-	-

Table L-4. Summary of Waste Types and Applicable Conditioning Technologies

Waste Type	Ambient or Low Temperature Thermal Technologies													Thermal Technologies								
	Solidification/ Encapsulation					Sorption - Cementation	Solidification		Encapsulation			De-watering		Stabilization				Melting		Vitrification		Containerization
	Cementation						Sorbents		Polymers									Metal Matrix		Glass Matrix		
	Portland cement (PC) and blended PC	Calcium aluminate cement	Calcium sulpho-aluminate cement	Phosphate cement	Geopolymers		Inorganic (clays)	Super-absorbent polymers	Thermo-plastics	Thermo-set	Bitumen	Drying / Crystallization	Calcining	Pyrolysis/Steam Reforming	Ceramics and Glass-ceramics	Hot isotactic pressing	Annealing	Powder binders	Metals / Alloys	Silicate glass	Phosphate glass	
Solids																						
Dry particulate (incinerator ash)	M	L	L[(1)]	D	L	-	-	-	M	M	M	-	-	D	L	M	-	-	-	D	L	M
Misc. dry solids	M	L		D	-	-	-	-	M	M	-	-	-	-	-	-	-	-	M	D	-	M
Organic solids	M	-	-	-	-	-	-	-	M[(2)]	-	-	-	-	-	-	-	-	-	-	-	-	M
Metallic solids	M	-	-	L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	M	D	-	M
Bulk solids, discarded equipment, objects, and compacted waste	M	-	-	D	-	-	-	-	-	M	M	-	-	-	-	-	-	-	-	D	-	M
Disused sealed sources	M	-	-	-	-	-		-	-	-		-	-	-	-	-	-	-	M	-	-	M
Problematic wastes																						
Reactive metals (Mg, Al, U)	M (Mg) (D U)	L (Al)	L(Al)	L (Mg, U)	D (Mg)	-	-	-	-	-	-	-	-	Oxidation				D	-	D (Mg)	-	M
Mixed waste (toxic and radioactive Be, Hg, asbestos, PCBs)	M	-	-	M	-	-	-	-	-	-	-	-	-	D	-	-	-	-	-	asbestos	-	M
Tritiated solids	M	-	-	-	D	-	-	-	M	-	-	-	-	-	-	-	-	-	-	-	-	M
Tritiated liquids	M[(4)]	L	-	L	D	M	M	D	L	-	-	-	-	-	-	-	-	-	-	-	-	M
Graphite blocks	M	-		-	L	-	-	-	-	D	D	-	-	D	-	-	M	-	-	L	-	D[(5)]
Na/K waste[(3)]	D		-		D	-									D					D		
Biological wastes (medical, research)	M	-	-	-	-	-	-	-	-	-	-	M		Destruction (Incineration, Chemical)				-	-			M
NORM and mining wastes	M	-	-	-	D	-	-	--	-	-	-	-	-	-	-	-	-	-	-	-	-	M
D&D debris (concrete, metal)	M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	M	M	-	M
Environmental waste (soils, sludges, sediments)	M	-	-	D	D	-	M	-	-	-	-	-	-	-	-	-	-	-	-	M	-	M
Accidental (large volume)	M	-	-	-	M	-	M	--	-	-	-	-	-	-	-	-	-	-	-	M	-	M

Source: IAEA, 2022, *Conditioning Handbook*, Draft, International Atomic Energy Agency, Vienna, Austria.
Note (1) – ashes from incineration of technological wastes with neoprene and PVC containing significant soluble zinc chloride
Note (2) – mature and demonstrated for PPE treated at slightly elevated temperature
Note (3) – Na/K wastes require pretreatment to neutralize the alkali metal prior to solidification
Note (4) – polymer-impregnated concrete has also been utilized for this purpose
Note (5) – direct placement of graphite blocks in a geological disposal facility is considered an option, with or without containerization.
M = Technology is mature and widely applied (TRL 8-9)
D = Technology is under development or limited use (TRL 3-7)
L = Lab scale studies only (TRL 1-2)
(-) = No current known use

Many examples of low temperature immobilization/grouting are present throughout the global nuclear community. Select examples include the following (IAEA-TECDOC-1701, *The Behaviors of Cementitious Materials in Long Term Storage and Disposal of Radioactive Waste – Results of a Coordinated Research Project*):

- Australia has used concrete and other mixes for low level waste.
- Belgium will use a Portland cement overpack around glass canisters.
- Brazil has used cement encapsulation of sealed sources, solids, and liquid wastes.
- China has immobilized spent resins and LLW using calcium sulfoaluminate or OPC with modifications.
- Czechia has used "geocement" and OPC blends for ion exchange resins and nuclear power plant wastes.
- Egypt has used cementation for LLW and intermediate level waste (ILW).
- Finland has used an OPC/fly ash blend for ion exchange resins.
- France has many uses, including spent cladding, zinc wastes, liquids, and oils.
- Hungary, Slovenia, South Africa, Switzerland, Ukraine, India, South Korea, and Romania have used OPC grout with different modifications for nuclear power plant LLW and ILW.
- Russia has used OPC for sludges and salts.
- Serbia is using modified OPC to focus on cesium and strontium leachability.
- The U.K. uses include Magnox sludge and nuclear power plant LLW and ILW.
- France, Germany, the Czech Republic, and Russia have solidified evaporator concentrates as cementitious waste forms.
- The Marcoule liquid waste treatment facility in France has pioneered the immobilization of sludges and oils in cementitious matrices.

This extensive application of low temperature solidification processes (grout) around the world lends a high degree of confidence in further implementation at the Hanford Site.

L.11 CLOSURE WASTE TANKS USING FLOWABLE GROUT

Following completion of waste retrievals from storage tanks, the remaining tank and any residuals are contaminated and should be stabilized for infrastructure stability and to prevent intrusion or future leaks. The previous DOE experience in tank closure grouting is relevant to this study as the assessment criteria related to residual toxicity and tank leak risk are impacted by these processes. The properties of the tanks having been previously closed with grout by DOE (contaminated, held reprocessing waste) are similar to the eventual retrieved tanks at Hanford.

L.11.1 Closure of U.S. Department of Energy High-Level Waste Tanks Using Flowable Grout

Cementitious grouts and flowable concretes are used to physically stabilize contaminated HLW tanks and other underground structures, which if not filled would eventually result in collapse or subsidence of overburden and protective engineered cap. In addition to physically stabilizing the tanks, these grouts are formulated to chemically stabilize radionuclides by providing a chemical and mineralogical environment that fixes mobile isotopes in or on the grout matrix phases. Examples of DOE tank closure grouts are provided in the subsections that follow.

L.11.1.1 Savannah River Site

Four types of HLW tanks exist at SRS – Types I, II, III, and IV (Langton, 2018a). Eight of these tanks have been closed, or successfully filled with grout. Tanks 17 and 20 in the F-Area Tank Farm were the first two to close (closed in 1997) – both were Type IV (no cooling coils) and were filled with a stabilizing (reducing) grout, a structural (bulk fill) grout, and a capping (strong) grout (Figure L-2 and Table L-5). The original concept was to use a high strength reducing grout to encapsulate the residual waste, a controlled low-strength material (CLSM)[1] for filling the bulk of the tank and a 2000 psi grout as an intruder barrier in the top of the tank.

The original SRS CLSM and 2000-psi grout mixes were modified by SRNL to eliminate bleed water (WSRC-STI-2007-00641, *Grout Formulations and Properties for Tank Farm Closure (U)*).

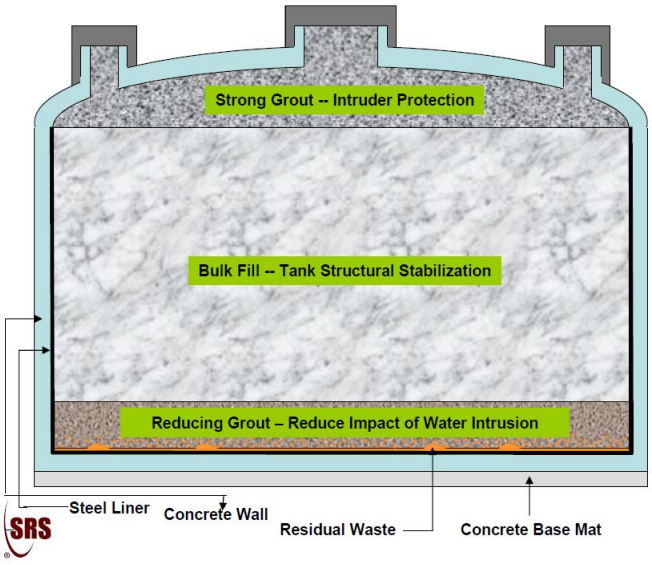


Figure L-2. Tank Closure Concept for Type IV High-Level Waste Tanks

Table L-5. Savannah River Site Tank Closure Grout Mix Designs from the 1990s

Ingredient	SRS Reducing Grout	SRS Zero-Bleed Flowable Fill	SRS Zero-Bleed 2000 psi Grout	All-In-One Zero-Bleed Reducing Fill/Grout[b]
Portland Cement, Type I/II (lb/yd^3)	1,353	150	550	75
Slag Grade 100 (lb/yd^3)	209	---	---	210
Fly Ash, Class F (lb/yd^3)	---	500	---	
Silica Fume (lb/yd^3)	90	---	---	---
Quartz Sand, ASTM C33 (lb/yd^3)	1,625 masonry sand	2,300 concrete sand	2,285 concrete sand	2,300 concrete sand
Water (gal/yd^3)	86.4	63	65	60
HRWR – ADVA® Flow (fl oz./yd^3)[a]	250	90	140	90
Viscosifier – Kelco-crete® (g/yd^3)[a]	---	275	275	275
Set Retarder (fl oz./yd^3)	150	---	---	---
Sodium Thiosulfate (lb/yd^3)	2.1	---	---	2.1 (optional)

Source: WSRC-STI-2007-00641, 2007, *Grout Formulations and Properties for Tank Farm Closure (U)*, and WSRC-TR-2001-00359, 2001, *State of the Art Report on High-Level Waste Tank Closure (U)*, Washington/Westinghouse Savannah River Company, Aiken, South Carolina.

[a] HRWR (ADVA® Flow) and Kelco-crete® were premixed prior to incorporation in the zero-bleed mixes.

[b] This mix was developed for future HLW tank closures. The mix proportions can be adjusted to obtain a range of compressive strength suitable for waste encapsulation, bulk fill, and intruder protection.

HLW = high-level waste. SRS = Savannah River Site.
HRWR = high-range water reducer.

[1] CLSM is a cementitious, flowable fill that is used as backfill or infill and has soil-like properties. The material is self-compacting and consequently does not require mechanical compaction to achieve design density. CLSM typically contains sand, fly ash, and less than 100 lb of hydraulic material per cubic yard of fill. Hydraulic cementitious material reacts with water to form insoluble hydrated compounds. Portland cement is the best-known hydraulic cement. Slag cement is also hydraulic once it has been activated.

Initial testing of the site CLSM and 2000 psi grout indicated that a significant amount of bleed water would be generated in the closed tanks. In early 1997, SRNL and Bechtel Savannah River, Inc. personnel were requested to modify the site CLSM mix and 2000 psi mix to eliminate the need for removing and disposing of radioactively contaminated liquid from the tanks and to improve uniformity of the fill material (reduce settling and stratification). The resulting modified mixes were referred to as SRS zero bleed flowable fill and SRS zero-bleed 2000 psi grout (see Table L-5).

In 1998, research was conducted to develop an all-in-one HLW tank fill grout that could be used for both encapsulating the residual waste and bulk fill (WSRC-STI-2007-00641; WSRC-TR-98-271, *Laboratory and Field Testing of High Performance Zero Bleed CLSM Mixes for Future Tank Closure Applications (U)*). The driver for this work was the desire to simplify the production requirements for tank fill material. This work resulted in an all-in-one zero bleed reducing fill/grout mix (also provided in Table L-5).

Unlike Type IV tanks, tanks of Types I, II, III, and IIIA at SRS contain cooling coils (WSRC-STI-2008-00172, *Closure of HLW Tanks – Formulation for a Cooling Coil Grout*). The ability to successfully fill intact cooling coils with grout depended on developing a grout formulation that satisfied the processing requirements for filling HLW tank cooling coils (WSRC-STI-2008-00298, *Closure of HLW Tanks – Phase 2 Full Scale Cooling Coils Grout Fill Demonstrations*). The cooling coil grout composition developed and tested is provided in Table L-6, along with its physical properties. The MasterFlow® (MF) 816 cable grout was obtained from BASF, Inc., and the Grade 100 blast furnace slag from Holcim, Inc.

Table L-6. Cooling Coil Cable Grout Composition and Physical Properties

Component	Mass fraction
MasterFlow® 816 cable grout	0.6767
Blast furnace Grade 100 slag	0.0752
Water	0.2481
Density using pycnometer (g/mL)	2.07
Water to cementitious mass ratio	0.33
Flow cone (seconds) at 23°C	20–30

Both the MF 816 and slag are cementitious materials. A unique characteristic of this grout is that it has a fairly long working time such that its physical properties change little over an extended period of time. The rheological properties, both yield stress and plastic viscosity, over a period of 90 minutes of continuous mixing, were essentially constant (WSRC-STI-2008-00172). This grout also satisfied the piping pressure limit of 150 psig during grout fill, for 1,200 linear feet of 2-in. Schedule 40 piping (G-CLC-G-00111, "Calculation of Permissible Rheology Range for Cooling Coil Grout"). The condition of flow for this grout is laminar for flow rates up to 200 gal/min, but the actual flow rate will be lower due to the piping pressure limit.

Type I tanks contain 34 vertical cooling coil assemblies (half primary, half auxiliary) and two horizontal cooling coil assemblies (one primary, one auxiliary) (WSRC-STI-2008-00298). For the vertical coils, the assemblies contained 180-degree, 2-ft radius bends. The vertical distance between the top and bottom of the 180-degree, 2-ft radius bends is 22.5 ft. The horizontal assemblies also had 90-degree bends to get around the support columns in the tank. The SRS Type I tank linear piping runs vary 2.75 to 65 ft between bends (90-degree bends connected with 2.75 ft of piping). Full-scale mockup testing was performed at the Clemson Engineering Technologies Laboratory for grouting cooling coil piping to demonstrate the effectiveness of completely filling the piping with grout.

The cooling coils were filled with an aqueous solution of chromate and sodium hydroxide, and there was concern that residual liquid of that mixture could adversely impact grout properties (e.g., compressive strength). Tests were conducted with a batched simulant (MF 816 + slag) containing chromate (0.006 M) and sodium hydroxide (0.001 M) at a water to cementitious mass ratio of 0.33. Even with a conservatively high amount of chromate and free hydroxide in the cooling coil solution, acceptable grout properties were demonstrated to be obtained in the presence of residual chromate and free hydroxide in the water (WSRC-STI-2008-00172).

Using these proven grouts that have been developed, four HLW tanks with cooling coils and four tanks without cooling coils have been closed at SRS (Table L-7).

Table L-7. Savannah River Site High-Level Waste Tank Closures

Tank	Type	Date Closed
20 F	IV	7/28/1997
17 F	IV	12/10/1997
18 F	IV	9/5/2012
19 F	IV	9/5/2012
5 F	I	12/19/2013
6 F	I	12/19/2013
16 H	II	9/23/2015
12 H	I	4/28/2016

L.11.1.2 Idaho National Laboratory

In 1953, the Idaho Chemical Processing Plant, now the Idaho Nuclear Technology and Engineering Center (INTEC) at Idaho National Laboratory (INL), was chartered to recover fissile uranium by reprocessing spent nuclear fuel (Butterworth and Shaw, 2009). In 1992, DOE officially discontinued reprocessing spent fuel at INTEC. The Tank Farm Facility (TFF), located within the northern portion of INTEC, comprises eleven 1,135.6 kL (300,000-gal) below-grade stainless steel tanks in unlined concrete vaults of various construction, four inactive 113.5 kL (30,000-gal) stainless steel tanks, interconnecting waste transfer piping, and ancillary equipment. The TFF tanks had been used to store a variety of radioactive liquid waste, including wastes associated with past spent nuclear fuel reprocessing.

The four 113.5 kL (30,000-gal) (Tanks WM-103, -104, -105, and -106) and seven 1,135.6 kL (300,000-gal) (Tanks WM-180, -181, -182, -183, -184, -185, and -186) TFF tanks were emptied of waste, cleaned, and grouted in place in 2006 and 2007 (Butterworth and Shaw, 2009). Ancillary piping and valve boxes associated with these tanks were grouted in 2008. Over 24,000 yd^3 of grout were placed to fill the tanks and vaults, followed by the grouting of over 7 miles of underground process and cooling coil piping. The TFF remains operational to provide interim storage of radioactive liquid waste awaiting final treatment, and closure of the remaining four large tanks has yet to be accomplished.

The ingredients and proportions for the grout fill formulations at the INTEC TFF are listed in Table L-8 (WSRC-TR-2001-00359, *State of the Art Report on High-Level Waste Tank Closure (U)*). One grout was for filling pipes (pipe grout) and the other was for filling the bulk of the tanks and vaults (tank grout).

Table L-8. Grout Compositions for Closing Tanks at the INTEC Tank Farm Facility

Ingredient	Pipe Grout	Tank Grout
Portland Cement, Type I/II (lb/yd^3)	680	320
Fly Ash, Class F (lb/yd^3)	1,600	640
Quartz Sand (lb/yd^3)	-	2,200
Water (gal/yd^3) *(lb/yd^3)*	96 max. *(800 max.)*	52 max. *(433max.)*

INTEC = Idaho Nuclear Technology and Engineering Center.

L.11.2 Other Waste Tank Closure Examples Using Flowable Grout

L.11.2.1 Savannah River Site

Closure of the Consolidated Incineration Facility

Operation of the SRS CIF ended in November 2000 when operation was deemed not economical for PUREX treatment (ERD-EN-2009-0101). Four 14 m^3 (30,000-gal) underground solvent storage tanks, Tanks 33–36, were part of the CIF (Langton, 2018b). Those tanks were filled with a self-leveling, zero bleed grout between May 29 and June 27, 2018. A total of 135 to 140 yd^3 of grout were placed in each tank (two lifts, 7 days apart) (Figure L-3 and Figure L-4).

Figure L-3. Consolidated Incineration Facility Solvent Tank Grouting

Figure L-4. Tank #34, Grout Nearing the Top

L.11.2.2 Oak Ridge National Laboratory

Closure of the Gunite and Associated Tanks

Several underground storage tanks were constructed in the Gunite and Associated Tanks (GAAT) Operable Unit (OU) between 1943 and 1951, designed to store liquid radioactive chemical wastes generated by ORNL operations (ORNL/TM-2001/142/V1, *The Gunite and Associated Tanks Remediation Project Tank Waste Retrieval Performance and Lessons Learned*). A total of twelve gunite tanks (Note: Gunite is a mixture of Portland cement, sand, and water, which was sprayed over a wire mesh and steel reinforcing rod frames) and four stainless-steel tanks were constructed, primarily in the North and South Tank Farms (Table L-9).

Table L-9. Tanks Located in the Gunite and Associated Tanks Operable Unit

Tank number(s)	Construction material	Date stabilization with grout completed
W-11	Gunite	2000
TH-4	Gunite	April 2001
North Tank Farm Tanks		
W-1 and W-2	Gunite	2000
W-13, W-14, W-15	Stainless-steel	FY 1998
W3 and W4	Gunite	September 2001
W-1A[a]	Stainless-steel	N/A
South Tank Farm Tanks		
W-5, W-6, W-7, W-8, W-9, W-10	Gunite	September 2001

Source: ORNL/TM-2001/142/V1, 2003, *The Gunite and Associated Tanks Remediation Project Tank Waste Retrieval Performance and Lessons Learned*, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[a] Tank W-1A was not stabilized/grouted in place as the other GAAT OU tanks. Due to leaks in the tank's waste transfer lines, Tank W-1A and surrounding contaminated soil(s) was excavated and removed (shipped offsite for disposal) in January 2012.

GAAT = Gunite and Associated Tanks.
N/A = not applicable.
OU = Operable Unit.

The GAATs were stabilized in place and filled with a low-strength grout (Table L-10) (ORNL/TM-2001/142/V1).

Table L-10. Grout Formulation used for Filling the Gunite and Associated Tanks

Ingredient	Amount (lb)	% of total (wt%)
Portland cement	1.4	2.2
Sand	48.8	76.5
Water	13.6	21.3
Total:	63.8	

Source: ORNL/TM-2001/142/V1, 2003, *The Gunite and Associated Tanks Remediation Project Tank Waste Retrieval Performance and Lessons Learned*, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Closure of the Old Hydrofracture Facility Tanks

Five underground, carbon-steel tanks were constructed at the Old Hydrofracture Facility and were in service from 1963 through 1980 (Tanks T-1, T-2, T-, T-4, and T-9) (ORNL/TM-2000/7, *Oak Ridge National Laboratory Old Hydrofracture Facility Tank-Closure Plan and Grout-Development Status Report for FY 1999*). A small residual waste volume remained in each tank after the wastes (sludge and supernatant liquid) were retrieved. A two-stage grouting process was used to stabilize these tanks – the initial stage targeted blending the residual waste with grout; the second bulk-fill stage filled the remaining tank structure (reference pending). The bulk-fill grout formulation is shown in Table L-11. This flowable grout had the following purposes: to provide structural stability to the tanks, prevent subsidence and further additions to the tanks, and add waste-retention properties for the RCRA and radioactive constituents present in the tank heel.

Table L-11. Old Hydrofracture Facility Tank Grout Formulation

Ingredient	Amount
Portland cement, Type II (lb/yd^3)	50
Fly Ash, Class F (lb/yd^3)	600
Concrete Sand (lb/yd^3)	2,400
Water (gal/yd^3) *(lb/yd^3)*	50 *417*

Source: ORNL/TM-2000/7, 2000, *Oak Ridge National Laboratory Old Hydrofracture Facility Tank-Closure Plan and Grout-Development Status Report for FY 1999*, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

L.11.3 Hanford Grout Mix Development for Tank Closures

Hanford's closure configuration is assumed to be similar with the successful demonstrations being conducted at SRS and INL (Case, 2012; SRR-LWP-2009-00001, *Liquid Waste System Plan*; CNWRA 2009-001, *Review of Literature and Assessment of Factors Relevant to Performance of Grouted Systems for Radioactive Waste Disposal*). The overall approach for dispositioning the tank wastes at Hanford, SRS, and Idaho National Laboratory has been to remove the waste to the maximum extent practical and separate the waste into high and low activity fractions.

In 2002, the first set of tanks identified for closure included Tanks C-106, C-201, C-202, C-203, C-204, S-102 and S-112 (WSRC-TR-2004-00021, *Stabilizing Grout Compatibility Study*; RPP-11094, *Tank Closure Fill System for the Accelerated Tank Closure Demonstration Level 2 Specification*). This includes waste retrieval, tank cleaning, and filling the empty tanks with Portland cement-based materials. Three grouts were designated for the tank fill:

- Stabilizing grout (Phase 1 Grout) to eliminate residual liquid in the tanks and stabilize contaminants (^{99}Tc) in the residual tank heels
- Structural grout (Phase 2 Grout) to provide structural support for the landfill (filling the tank void space)
- Capping grout (Phase 3 Grout) to provide an intruder barrier at the top of the tanks.

To date, a conclusive grout formulation for Hanford tank closure has yet to be finalized, and no tanks have been closed from a regulatory standpoint (the list of tanks designated for closure has also evolved). There has been work performed to target stabilization of tank residuals through grout formulation or redox control (Cantrell et al., 2014).

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Appendix M. FFRDC Team Response to the National Academies of Science, Engineering, and Medicine Final Report on the NDAA17 3134 Draft Report

M.1 INTRODUCTION

This appendix provides the Fiscal Year (FY) 2021 National Defense Authorization Act (NDAA21) Section 3125 Federally Funded Research and Development Center (FFRDC) team's response to the findings and recommendations from the National Academies of Science, Engineering, and Medicine (NASEM) final report – review of the NDAA17 Section 3134 FFRDC draft report (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*). The FFRDC team reviewed the NAS report from the initial analysis to be familiar with the findings and recommendations and to incorporate aspects from the final NAS report into this analysis as appropriate. Table M-1 summarizes the findings/recommendations and associated response.

Table M-1. FFRDC Team Response to NAS Final Report (NDAA17 3134)

NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
Summary/3 Summary/37 Committees Findings/69	Finding 1-1	The purpose of the committee's review is to advise whether DOE, Congress, regulators, and other stakeholders can rely on the FFRDC report to evaluate and decide on a treatment approach for the SLAW. The committee finds that, in its current iteration, the FFRDC's analysis: a. When taken alone, does not yet provide a complete technical basis needed to support a final decision on a treatment approach; b. Does not yet clearly lay out a framework of decisions to be made among treatment technologies, waste forms, and disposal locations; but c. Can form the basis for further work as described below in the committee's findings and recommendations.	a. The FFRDC team agrees that the final report did not yet provide a complete technical basis to support a final decision, especially regarding on-site disposal. Technical uncertainties that remained with the most promising alternatives (e.g., grouted supplemental LAW for on-site disposal, lowest cost and shortest schedule) make a complete technical basis difficult to determine for the NDAA17 3134 report (SRNL-RP-2018-00687[a]). The NDAA21 3125 study (this report) characterizes the remaining technical uncertainties and their likelihood of successful resolution and maturation. b. The FFRDC team agrees. A decision framework was not within the scope of the FFRDC task under NDAA17 3134. The NDAA21 3125 study (this report) develops and describes a framework of decisions. c. The FFRDC team agrees. DOE and its contractors pursued additional supplemental LAW work after the NDAA17 3134 final report[a] to address several findings and recommendations.
Summary/4 Summary/37 Committees Findings/69	Finding 2-1	The cost estimates in the FFRDC report are based on technologies that, for the most part, have not yet been fully developed, tested, or deployed for Hanford's particular, and particularly complex, tank wastes, and instead use costs from similar technologies. As a result, there are large attendant uncertainties, suggesting that costs could be much higher than estimated, but are unlikely to be much lower.	The FFRDC cost estimates in the NDAA17 3134 report[a] were based on costs from similar applications of these technologies on tank wastes and have been tested at smaller scale on representative Hanford tank wastes. The technologies have not been fully developed or deployed for treating the Hanford supplemental LAW. Use of the "+100%" high-end range provided the contingency above point estimates. For the NDAA21 3125 study (this report), the same range of costs is used, along with evaluation of potential timing impacts due to flat funding – as used for WTP construction.

Table M-1. FFRDC Team Response to NAS Final Report (NDAA17 3134)

NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
Summary/4 Summary/37 Committees Findings/69	Finding 2-2	The cost estimates in the FFRDC report are based on continuing funding at and beyond current levels to optimize the waste treatment technologies and speed of progress. These involve very large annual appropriations, which are inevitably uncertain over the planned decades of activity, especially because current planning assumptions anticipate a two- or three-fold increase in expenditures at certain points in the SLAW treatment process. This, too, introduces the possibility that funding shortfalls will lead to longer schedules, increased total costs, and higher chances of additional tank leaks or structural failures, which will themselves increase costs as well as health and environmental risks.	The FFRDC team agrees. The NDAA17 3134 report[a] highlighted the annual cost and historic funding profile to emphasize the likely financial appropriation risks associated with the current baseline. This description also highlighted that with any supplemental LAW treatment alternative, the required cost profile for the balance of facilities, including HLW treatment, still exceeds past funding levels. The NDAA21 3125 study (this report) is explicitly including alternatives such as grout hybrid options not addressed in 2019 and evaluation criteria that better enable consideration of accelerated treatment that would reduce risks associated with continued aging of existing tank infrastructure.
Summary/4 Summary/38 Committees Findings/69	Finding 2-3	The report's analysis of costs does not enable the reader to analyze key trade-offs among specific alternatives or variations of major alternatives.	The current NDAA21 3125 task allows for more definitive analysis as the feed vector is not static and the impact of facility costs with respect to project initiation can be modeled. Likewise, process technology variations and hybrid options are included.
Summary/4 Summary/38 Committees Findings/70	Finding 3-1	Assessment of waste form performance would have to include consideration of the characteristics of the disposal sites and the transport pathways to receptors over relevant periods of time, as well as be based on the inherent characteristics of the waste form.	The FFRDC team agrees. The NDAA17 3134 report[a] presented the approach and results of a performance evaluation that included characteristics of Hanford's on-site IDF, the primary transport pathway to receptors (groundwater) for 1,000 years post-closure (DOE compliance timeframe), and peak concentration (post-compliance), and relied on inherent characteristics of each supplemental LAW waste form based on the most recent, relevant studies. For off-site disposal, a performance evaluation approach was not necessary, because robust waste acceptance criteria were already established based on that disposal facility's PA that had included the site's characteristics, transport pathways, inventory, and waste form characteristics. Additionally, the NDAA21 3125 effort includes some discussion regarding long-term assumptions used in PA development for the off-site disposal facilities considered.

Table M-1. FFRDC Team Response to NAS Final Report (NDAA17 3134)

NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
Summary/4 Summary/38 Committees Findings/70	Finding 3-2[1]	The committee did not have access to the 2017 IDF PA that has been prepared by DOE or to the Performance Evaluation (PE) data and analysis prepared by the FFRDC. Therefore, it was impossible for the committee to critically review the differences in the performance of the three waste forms and their associated disposal systems over time. Additionally, the technical bases for waste degradation models and mechanisms used in the PE analyses for the IDF by the FFRDC team are not well documented and justified.	The FFRDC team understands that the committee received both the IDF PA[b] and FFRDC PE[c] late in the NDAA17 3134 process. The waste degradation models and mechanisms used in the PE analyses were substantially consistent with those documented in both the current and past IDF PAs, and in referenced literature. The justification for updated or modified degradation models and model parameters were included in the NDAA17 3134 report.
Summary/4 Summary/38 Committees Findings/70	Finding 3-3[2]	Without the proper supporting documentation for the FFRDC's PE, or the IDF PA on which it was based, the committee is unable to assess the potential significance of mobile, long-lived fission products such as iodine-129, technetium-99, and other long-lived radionuclides (possibly selenium-79 and others). It would have been useful for the FFRDC to include the human health risk estimates (dose) over time for all of the long-lived radionuclides that are listed in Table F-2 of their report, not just iodine-129 and technetium-99.	The IDF PA[b] included information on all of the long-lived radionuclides for the base vitrification case, and both the IDF PA and the TC&WM EIS[d] results reflect that ^{129}I and ^{99}Tc are the principal drivers for groundwater impact. The NDAA17 3134 report[a] added a Figure F-5 (page 182) to show the peak IDF PA impacts of all long-lived radionuclides for the baseline vitrification supplemental LAW case. ^{99}Tc and ^{129}I are the dominant contributors to the groundwater pathway dose between 1,000 and 10,000 years. ^{79}Se and ^{226}Ra contribute to total groundwater pathway dose much later (>100,000 years), and to a lower level than either ^{99}Tc or ^{129}I. Non-glass supplemental LAW waste forms may result in different peak dose values and time to peak. However, based on the IDF PA[b] and EIS[d] results and total inventory of each long-lived radionuclide, there is no evidence that ^{99}Tc and ^{129}I will not continue to be the primary contributors to dose.
Summary/5 Summary/38 Committees Findings/70	Finding 3-4	The FFRDC report gives little consideration in its analysis to the environmental, health, and safety consequences of hastening or further delaying remediation of the Hanford waste storage tanks, which is related to the probability that additional tank leaks or structural failures will occur over the long period of time expected for the removal and treatment of the waste in the tanks.	The FFRDC team agrees. Risk of additional tank leaks or structural failure was outside the scope of the FFRDC NDAA17 3134 study.[a] This is a consideration in this NDAA21 3125 report, principally from the perspective of alternatives that could help accelerate waste treatment and thereby reduce risks associated with continued aging of the existing Hanford tank infrastructure.

[1] The committee notes that subsequent to publication of Review #3, it received access to the PA. See the discussion in Chapter 2 of this review report for the committee's observations about relevant aspects of the PA and about what was available in the FFRDC final report on the PE.

[2] See the previous footnote about the committee's views on the PA and the PE as discussed in Chapter 2.

Table M-1. FFRDC Team Response to NAS Final Report (NDAA17 3134)

NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
Summary/5 Summary/38 Committees Findings/70	Finding 4-1	The FFRDC performed an analysis of whether removal of iodine-129 and technetium-99 was needed to comply with the disposal waste acceptance criteria, and examined the status of technologies for removing these radionuclides from the SLAW feed stream, but the FFRDC report does not respond fully to the congressional direction (in Sec. 3134) because the report does not address immobilization of the iodine-129 and technetium-99 recovered from the LAW as part of the separate high-level glass waste form to be produced in the WTP.	The FFRDC team concurs. ^{99}Tc and ^{129}I that could be separated from the LAW feed prior to LAW immobilization could potentially be eluted from pretreatment media in a concentrated form and fed to the HLW melter(s). An elutable media or precipitation method for removing ^{129}I from LAW has not been developed, but an inorganic sorbent has exhibited effectiveness in initial laboratory simulant testing. Both long-lived radionuclides will face similar volatilization issues in the HLW melters as in the LAW melters, partition principally to the offgas system, and likely result in similar total levels in secondary waste destined for the IDF. Off-site disposal of more concentrated eluted ^{99}Tc and ^{129}I from pretreatment media may be more beneficial than transferring to the HLW feed stream. The NDAA21 3125 study (this report) discusses the complex issue of technetium and iodine separation and disposition that is the major contributor to the projected peak groundwater concentration of ~400 pCi/L (below the 900 pCi/L MCL). The largest inventory of ^{99}Tc is in the LAW glass (26,400 Ci) and contributes ~100 pCi/l to the total. Therefore, the likely groundwater impact of removing ^{99}Tc from the LAW feed and transferring it to the HLW feed would be similar to or possible reduction in the smaller ILAW contribution (~25%) to groundwater.
Summary/5 Summary/39 Committees Findings/70	Finding 5-1	The report makes little use of the experience with grouting and other technologies at other DOE sites and commercial operations. While there are unquestionably meaningful differences among the waste forms, technologies, and disposal environments as compared to Hanford, the extensive experience gained at Savannah River Site, in particular, is an invaluable source of insight.	The FFRDC team disagrees. The study team applied significant information and experience from grouting of salt waste at SRS to this study, including maturity and costs of the process used, and the waste formulation, waste form performance data, and disposal site similarities and PA methods, where appropriate. However, the NDAA17 3134 report[a] did not focus on highlighting the information derived from SRS work in the grout discussion and did not list similarities or differences between SRS and Hanford wastes, because the work was not considered important to the study results or conclusions.

Table M-1. FFRDC Team Response to NAS Final Report (NDAA17 3134)

NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
Summary/5 Summary/39 Committees Findings/70	Finding 5-2	The committee was repeatedly told that the selection and implementation of an approach to treat tank waste would be hampered by the insistence by the State of Washington and some other stakeholders that any approach other than vitrification must be "as good as glass." The term "as good as glass" is not defined in law, regulation, or agreement, and it is only tentatively defined by its advocates. The analysis in, and the public presentations of, the draft FFRDC reports offer a follow-on opportunity for DOE to engage with its regulators and stakeholders to identify performance standards based on existing regulatory requirements for waste form disposal and to pursue a holistic approach to selecting a treatment technology.	This finding is not related to the specific content of the FFRDC team's NDAA17 3134 effort.
Summary/5 Summary/39 Committees Findings/70	Finding 6-1	Over multiple iterations, the FFRDC report has increasingly enabled side-by-side comparisons among the SLAW treatment approaches, exemplified by the table of alternatives and criteria. It remains difficult, however, for the reader to see comparisons and trade-offs in the supporting narrative.	The FFRDC team agrees. Additional effort was made to provide that side-by-side summary comparison. The NDAA21 3125 study (this report) provides greater opportunity to better align the supporting narrative to appropriate comparisons, tradeoffs, and recommendations.
Summary/6 Summary/39 Committees Findings/70	Finding 7-1	The report represents useful steps forward by: a. Confirming that versions of vitrification, grouting, and steam reforming are treatment technologies that merit further consideration for the SLAW; b. Establishing the likelihood that vitrification, grouting, or steam reforming are capable of meeting existing or expected regulatory standards for near-surface disposal albeit with varying amounts of pre-treatment being required; c. Highlighting the important contribution of the iodine-129 in the secondary waste streams disposed at the IDF to the total estimated radiation dose rate to the receptors; d. Underscoring the regulatory and acceptance uncertainties regarding approaches other than vitrification technology for processing the SLAW	The FFRDC team agrees.

Table M-1. FFRDC Team Response to NAS Final Report (NDAA17 3134)

NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
		e. Opening the door to serious consideration of other disposal locations, specifically the WCS facility near Andrews, Texas, and possibly the Energy*Solutions* facility near Clive, Utah.	
Summary/6 *Summary/40 *Committees Recom-mendations/81 *Last sentence is not included here	Recom-mendation 1-1	The committee recommends that the "Preliminary Draft" FFRDC report reviewed by the committee (that is, the document dated April 5, 2019) be accepted as a pilot or scoping study for a full comparative analysis of the SLAW treatment alternatives, including: • Vitrification, grouting, and steam reforming as treatments for the SLAW; • Pre-treatment to remove iodine-129, technetium-99, and other long-lived radionuclides (e.g., selenium-79) to ensure that regulations are met or reduce cost, and pre-treatment to assure that the waste product meets land disposal requirements; • Pre-treatment of strontium-90, if it is not removed during the cesium-137 pre-treatment process; and • Disposal at the IDF, WCS, and (possibly) the Energy*Solutions* facility. The draft report should either be substantially revised and supplemented (though the committee understands that the FFRDC team's funding may not permit this), or be followed by a more comprehensive analysis effort and associated decisional document, which needs to involve the decision-makers or their representatives. This comprehensive analysis should adopt a total systems approach (one that includes addressing relevant externalities to SLAW that were outside the FFRDC's scope) to provide a substantially complete basis for decision-making.	The NDAA21 3125 study (this report) provides the opportunity to address many of these points in the follow-on analysis.
Summary/6 Summary/40 Committees Recom-mendations/82	Recom-mendation 2-1	The final FFRDC report or follow-on decisional document should include technical data and analyses to provide the basis for addressing four interrelated areas, as follows: a. Selection of a technology that will produce an effective waste form. This has two parts: • The treatment (immobilization) technology:	NDAA21 3125 follow-on study (this report) was structured to substantially address most aspects of the four interrelated areas identified in this recommendation, especially those aspects that were not noted in the findings and recognized as being addressed to a limited degree in the NDAA17 3134 report.[a] These aspects include: 1. Uncertainties and risks

Table M-1. FFRDC Team Response to NAS Final Report (NDAA17 3134)

NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
		– How well will it work? Is the technology well understood, tested or used under real-world conditions, dependent on other technologies, or relatively simple? – What types and volumes of secondary waste are created by each technology? – What is the lifetime cost and duration, and uncertainties therein? – What are the risks (e.g., programmatic and safety) and uncertainties therein? • The waste forms and associated disposal sites: – How effective is each waste form in immobilizing the waste (e.g., the materials science of the incorporation, corrosion, and release processes) and over what time periods? – What is their performance under the expected disposal conditions (e.g., release from the disposal facility and transport through the geosphere to a receptor)? – How do the waste form performances actually differ? This goes further than simply demonstrating compliance, but rather demonstrates an understanding of how the waste forms and disposal environments actually interact. The committee notes the limited amount of information and pervasiveness of uncertainty in many aspects of the decisions to be made. Although it may seem counter-intuitive, the committee suggests that probabilistic approaches be used in future analyses because, when information is limited, the result is in the form of uncertainties, which are very useful to decision-makers. b. Selection among available disposal sites. The report describes the IDF and WCS, and it briefly mentions the EnergySolutions facility near Clive, Utah. Selection requires an understanding of how each site will "work" over time in providing a barrier to the release and migration rate of key radionuclides, especially and specifically technetium-99 and iodine-129. • What is the role of the hydrogeology at each site (the IDF and WCS) in preventing/slowing radionuclide release and migration?	2. The materials science of incorporation, corrosion, and release processes from each waste form and understanding of waste form-disposal site interactions 3. Enhancing disposal site performance through modifications 4. Removing the technetium and iodine and alternate disposition paths 5. Accelerated treatment that can help reduce costs and risks of continued degradation of the Hanford tank infrastructure.

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		• How might the disposal facility design be modified to enhance the performance of each waste form? Important site-related issues include regulatory compliance, public acceptance, cost, safety, expected radiation dose to the maximally exposed individual over time, and differences among the disposal environments. c. Determining how much and what type of pre-treatment is needed to meet regulatory requirements regarding mobile, long-lived radionuclides and hazardous chemicals, and possibly to reduce disposal costs. The congressional charge specifically mentions technetium-99 and iodine-129, but other long-lived radionuclides, such as selenium-79, may be relevant. The analysis should consider both: • Leaving the technetium (Tc), iodine (I), and other long-lived radionuclides in the waste form for the SLAW, with possible use of enhanced engineered barriers such as getters, which are added materials that can better retain the contaminants of concern; and • Removing the Tc and I (and possibly other radionuclides) to create a new waste stream with its own (and possibly different) form of immobilization and final disposition, including incorporating it into the separate vitrified HLW stream. d. Other relevant factors. Other factors that would affect the selection of a SLAW treatment alternative include: • The costs and risks of delays in making decisions or funding shortfalls in terms of additional resource requirements and the increased chance of tank leaks or structural failures over time, and the need to address the consequences (notably, all 149 single-shell tanks have exceeded their design life and the 28 double-shell tanks will have exceeded their design life before the waste is slated to be removed); • DOE's proposed reinterpretation of the definition of HLW waste could change the SLAW size and performance requirements by altering the feed volume and composition depending on how the reinterpretation is implemented;	

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NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
		• Thorough consideration of the experience at other DOE sites (e.g., Savannah River Site) and relevant commercial facilities; and • Outcomes of DOE's proposed Test Bed Initiative, the second phase of which would have involved (and perhaps still could involve) grout treatment of 2,000 gallons of LAW and shipment to WCS (the first phase involved a proof of concept treatment of 3 gallons of LAW that was sent to WCS and was completed in December 2017). The future of the second phase of the Initiative is now in doubt due to DOE's withdrawal in late May 2019 of the state permit application	
Summary/8 Summary/42 Committees Recom-mendations/83	Recom-mendation 3-1	The analysis in the final FFRDC report and/or a comprehensive follow-on decisional document needs to adopt a structure throughout that enables the decision-maker to make direct comparisons of alternatives concerning the criteria that are relevant to the decision and which most clearly differentiate the alternatives.	The FFRDC team agrees. The NDAA21 3125 study (this report) adopted a structure and criteria that will enable decision-makers to make direct comparisons of alternatives.
Summary/8 Summary/42 Committees Recom-mendations/83	Recom-mendation 4-1	The FFRDC report could also provide the springboard for serious consideration of adopting an approach of multiple, parallel, and smaller scale technologies, which would have the potential for: a. Faster startup to reduce risks from tank leaks or structural failures if adequate funding is available to support parallel approaches; b. Resilience through redundancy (like the parallel uranium enrichment and plutonium separation methods during the Manhattan Project); c. Taking positive advantage of the unavoidably long remediation duration to improve existing technologies and adopt new ones; and d. Potentially lower overall cost and program risk by creating the ability to move more quickly from less successful to more successful technologies, with less stranded cost in the form of large capital facilities that are inefficient or shuttered before the end of their planned lifetime.	The FFRDC team agrees. The NDAA21 3125 study (this report) identifies alternatives that offer potential for multiple, parallel, and smaller scale (modular) approaches, offering the benefit of phased implementation and leveling of the funding profile.

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NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
Summary/8	Concluding Observa-tions	Based on its review of relevant aspects of the performance assessment of the IDF, the committee notes that the U.S. Environmental Protection Agency (EPA) drinking water standard (DWS) for iodine-129 and perhaps technetium-99 appears to be a key consideration in future decisions concerning the need for pretreatment to lower the concentrations of these two long-lived radionuclides and preferences for a particular waste form. This standard is based on radiation protection approaches dating from the 1950s and is no longer currently recommended by radiation protection authorities.	This topic is outside the scope of the FFRDC team's consideration under both the NDAA17 3134 and NDAA21 3125 scopes.
Summary/8	Recom-mendation 5-1	It would behoove DOE to consult with its regulators (particularly EPA and Washington State Department of Ecology) to determine whether risk-informing the current drinking water standard in terms of its underlying dosimetry and the assumed point-of-compliance is appropriate for application to SLAW disposal, or whether a more up-to-date standard for drinking water should be adopted. In view of the extent to which disposal decisions are driven by this standard, such a re-assessment would be well worth the effort.	See response to Concluding Observations, Summary/8.
		The committee concludes the Summary with noting key points from the stakeholder's and members of the public's comments. Many commenters expressed concern about placing long-lived radionuclides such as iodine-129 and technetium-99 in non-vitrified waste forms for near-surface disposal in the IDF at Hanford. A major driver of this concern is the potential hazard to drinking water and the river system, especially the Columbia River. Related to the concern about durability and waste retention of non-vitrified forms is the strongly held view among many commenters that vitrified waste forms would provide more protection for waste disposed at Hanford and is encapsulated in the saying "as good as glass." On the other hand, there is widespread interest in the potential for out-of-state disposal of non-vitrified waste forms.	The FFRDC team notes that constituents such as ^{129}I and ^{99}Tc are problematic in terms of being long-lived and low drinking water standards, and are volatile and difficult to immobilize. The current vitrification process uses a "flywheel" recycle process to increase incorporation of ^{99}Tc, and to a much lower extent ^{129}I into the glass matrix. Regardless of whether these species are being vitrified into ILAW or IHLW, they are not easily incorporated into the glass matrix, and substantial inventory is driven into secondary waste streams, especially ^{129}I. The NDAA21 3125 study (this report) further elucidates the challenges, uncertainties, and alternatives associated with treatment and disposal of these long-lived radionuclides in an effort to clearly enable decision-makers and stakeholder to compare the alternatives.

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NASEM Section/Page #	ID No.	Finding or Recommendation Text	FFRDC Team Response
		Finally, representatives of tribal nations and many members of the concerned and engaged public have clearly stated that decision-makers need to consider the entire ecosystem at Hanford and the potential for major climatic changes, massive flooding, and seismic activity, which might adversely affect waste disposal at Hanford.	

[a] SRNL-RP-2018-00687, 2019, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*, Savannah River National Laboratory, Aiken, South Carolina.
[b] RPP-RPT-59958, 2019, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*, Rev. 1A, Washington River Protection Solutions, LLC, and INTERA, Inc., Richland, Washington.
[c] Appendix F, Section F.4.3, "Disposal Performance Evaluation," of SRNL-RP-2018-00687.
[d] DOE/EIS-0391, 2012, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington*, U.S. Department of Energy, Office of River Protection, Richland, Washington.

DOE = U.S. Department of Energy.
DWS = drinking water standard.
EIS = environmental impact statement.
EPA = U.S. Environmental Protection Agency.
FFRDC = Federally Funded Research and Development Center.
HLW = high-level waste.
I = iodine.
IDF = Integrated Disposal Facility.
IHLW = immobilized high-level waste.
ILAW = immobilized low-activity waste.
LAW = low-activity waste.
MCL = maximum contaminant level.
NDAA = National Defense Authorization Act.
PA = performance assessment.
PE = performance evaluation.
SLAW = supplemental low-activity waste.
SRS = Savannah River Site.
Tc = technetium.
TC&WM = Tank Closure and Waste Management.
WCS = Waste Control Specialists, LLC
WTP = Waste Treatment and Immobilization Plant.

M.2 REFERENCES

DOE/EIS-0391, 2012, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington*, U.S. Department of Energy, Office of River Protection, Richland, Washington.

National Defense Authorization Act for Fiscal Year 2017, Public Law 114–328, December 23, 2016.

National Defense Authorization Act for Fiscal Year 2021, Public Law 116–283, January 1, 2021 (also known as the *William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021*).

RPP-RPT-59958, 2019, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*, Rev. 1A, Washington River Protection Solutions, LLC, and INTERA, Inc., Richland, Washington.

SRNL-RP-2018-00687, 2019, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*, Savannah River National Laboratory, Aiken, South Carolina.