Contract No:

This document was prepared in conjunction with work accomplished under Contract No. 89303321CEM000080 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

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

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April 2022

SRNL-STI-2022-00184, Rev. 0

DRAFT

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Printed in the United States of America

Prepared for
U.S. Department of Energy

Keywords: *Example keywords*

Retention: *Varies*

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

Name

Volume I
Month 2022 DRAFT

Savannah River National Laboratory is operated by Battelle Savannah River Alliance for the U.S. Department of Energy under Contract No. 89303321CEM000080.

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ACKNOWLEDGEMENTS

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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

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[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 since 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 would be a first-of-a-kind technology implementation, with the potential for substantial technical challenges.

Conversely, the FFRDC team found significant differences across the alternatives in cost, duration, and likelihood of successful project completion. The cost to implement capital projects for some of the proposed alternatives is likely unaffordable given current and planned budget profiles. Additionally, under expected budget scenarios, the implementation of several technologies would extend processing durations and increase the risk of further deterioration of the waste storage tanks due to the extended time necessary for waste storage and processing. Only alternatives employing grout technology appear to be technically viable, affordable, and flexible enough to implement under assumed constrained budget scenarios without significant impact to the WTP HLW Vitrification Facility mission completion schedule. Alternatives with off-site immobilization and disposal also offer some advantages. This finding is robust under the various 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 direct-feed low-activity waste (DFLAW) vitrification process.

This recommendation is based on a technical 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 affordability and robustness to technical risks), and (4) lifecycle costs (discounted). 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, including:

- Provides the capability to achieve the most rapid reduction in the amount of waste stored in the Hanford single-shell tanks (SST) and double-shell tanks (DST) 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 by most closely aligning with the annual planning budget and by reducing 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.

For adoption of this recommendation, regulatory and stakeholder participation procedures 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.

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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
^{266}Ra	radium-226
ACAA	American Coal Ash Association
AEA	Atomic Energy Act
ALARA	as low as reasonably achievable
AofA	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 Facility
BWF	Bulk Waste Disposal and Treatment Facilities
CA	Class A
CAA	Clean Air Act
CAC	calcium aluminate cement
CAN	Class A North
CAPEX	capital expenditure
CAW	Class A West
CD	Critical Decision
Cebama	cement-based materials
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CETL	Clemson Engineering Technologies Laboratory
CFMT	concentrator feed make-up tank
CFR	Code of Federal Regulations
CHT	calcined hydrotalcite
CIF	Consolidated Incineration Facility
CLSM	controlled low-strength material
CNWRA	Center for Nuclear Waste Regulatory Analysis
CoC	contaminant of concern
CoPC	constituent of potential concern
CORI	cement-organic-radionuclide interaction

Cr	chromium
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
CRR	carbon reduction reformer
CSA	calcium sulfoaluminate
CSSX	caustic-side solvent extraction
CST	crystalline silicotitanate
CSTR	continuous stirred tank reactor
CTE	critical technology element
CUA	Catholic University of America
CWA	Clean Water Act
CWF	cementitious waste form
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
DOE-ORP	U.S. Department of Energy, Office of River Protection
DOT	U.S. Department of Transportation
DRC	Division of Radiation Control
DRF	dry reagent formulation
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	State of Washington 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
EVS	ejector venturi scrubber

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
GDU	grout disposal unit
GFC	glass-forming chemical
GTCC	Greater-than-Class C
GW	groundwater
GWPL	groundwater protection level
GWQS	Ground Water Quality Standard
HDPE	high-density polyethylene
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
IP	industrial package
IQRPE	Independent Qualified Registered Professional Engineer
ISO	International Organization for Standardization
IWTU	Integrated Waste Treatment Unit
IX (IEX)	ion exchange

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

K_D	dissociation constant
Ksp	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
LDR	Land Disposal Restrictions
LDU	Land Disposal Unit
LERF	Liquid Effluent Retention Facility
LFE	LAW 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
MCDA	multiple-criteria decision analysis
MCL	maximum contaminant level
MCU	modular caustic-side solvent extraction unit
MDL	method detection limit
MF	MasterFlow®
MFHT	melter feed hold tank
MGS	modular grouting system
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
NPV	net present value
NRC	U.S. Nuclear Regulatory Commission
NSDWR	National Secondary Drinking Water Regulations
O	Order
OAG	Ogallala, Antlers, and Gatuna
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
ORR	Oak Ridge Reservation
OU	Operable Unit
PA	performance assessment
PCB	polychlorinated biphenyl
PCT	product consistency test
PE	performance evaluation
Perma-Fix	Perma-Fix Northwest, Inc.
PGF	process gas filter
PNNL	Pacific Northwest National Laboratory
PT	Pretreatment Facility
PUF	pressurized unsaturated flow
PV	present value
PUREX	plutonium-uranium extraction
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
SAC	sulfoaluminate cement
SALDS	state-approved land disposal site
SBS	submerged bed scrubber
SBWW	sodium-bearing wastewater
SCDHEC	South Carolina Department of Health and Environmental Control
SCPF	Scaled Continuous Processing Facility
SCR	selective catalytic reduction

SDU	Saltstone Disposal Unit
SDWA	Safe Drinking Water Act
Se	selenium
SER	Safety Evaluation Report
SLAW	supplemental low-activity waste
SMCL	secondary maximum contaminant level
SPFT	single-pass flow-through
SPRU	Separations Process Research Unit
sRF	spherical resorcinol-formaldehyde
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SST	single-shell tank
SSW	solid secondary waste
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
TOC	total organic carbon
TOE	total operating efficiency
TPA	Tri-Party Agreement
TPC	Total Project Cost
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
TWCSF	Tank Waste Characterization and Staging Facility
TWINS	Tank Waste Information Network System
U.K.	United Kingdom
U.S.	United States

UAC	Utah Administrative Code
UDEQ	Utah Department of Environmental Quality
UMTRA	Uranium Mill Tailings Remediation Action
UTS	Universal Treatment Standards
UV/OX	ultraviolet/oxidation
UWQB	Utah Water Quality Board
VHT	vapor hydration test
VLAW	vitrified low-activity waste
VOC	volatile organic compound
VSL	Vitreous State Laboratory of The Catholic University of America
VTD	vacuum thermal desorption
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
WV	West Valley
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 (TBI) 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) 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[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 of LAW includes filtration for solids removal and removal of cesium by ion-exchange using an elutable resin or absorption onto crystalline silicotitanate (CST). LAW treatment must include immobilization or separation of specific radionuclides that are long-lived (half-lives of hundreds of thousands of years or more) and mobile in the environment, such as ^{99}Tc and ^{129}I, to ensure long-term performance in a MLLW disposal facility that meets requirements for protection of human health and the environment.

[1] NDAA21 Section 3125, which governs the FFRDC follow-on report, refers back to NDAA17 Section 3134.
[2] The volume of waste to be treated is much greater than the volume currently in the waste tanks since 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 Restrictions (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 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 of tank waste in 2022.

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.

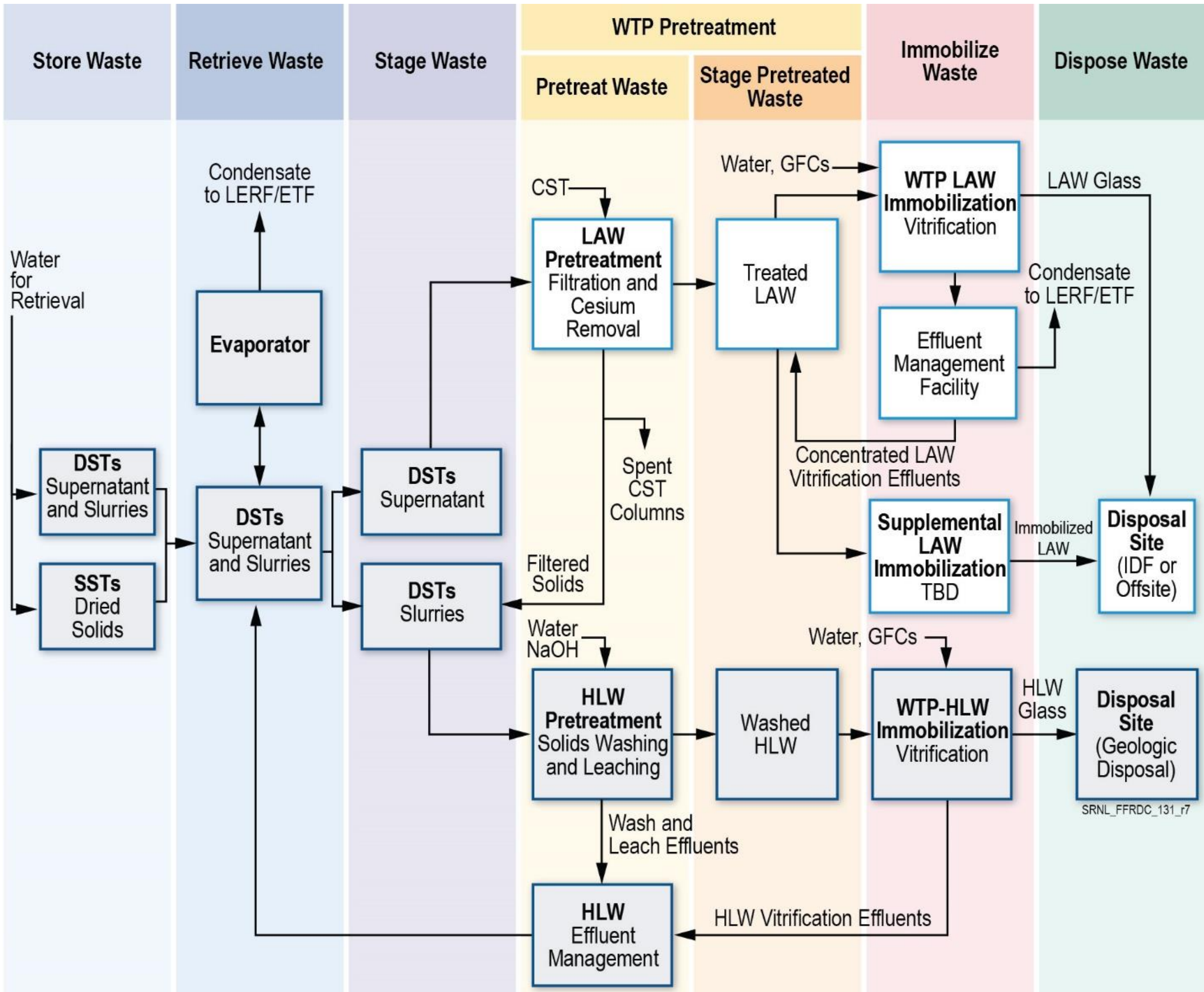
1.3 Process Overview

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 SSTs (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) configuration. The WTP Pretreatment (PT) Facility performs the pretreat and stage pretreated 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 pretreated 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 sent to a geologic disposal site at a location to be determined. 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.



CST	=	crystalline silicotitanate.	HLW	=	high-level waste.	NaOH	=	sodium hydroxide.
DST	=	double-shell tank.	IDF	=	Integrated Disposal Facility.	SST	=	single-shell tank.
ETF	=	Effluent Treatment Facility.	LAW	=	low-activity waste.	WTP	=	Waste Treatment and
GFC	=	glass-forming chemical.	LERF	=	Liquid Effluent Retention Facility,			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 sent to the Effluent Management Facility (EMF) where the effluents are evaporated.

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, achieved WTP LAW throughput, and the efficiency of existing facilities (e.g., tank farms, 242-A Evaporator, LERF/ETF) to manage single-shell tank (SST) retrievals, waste staging and characterization, and effluent treatment.

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. 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 significantly impact the volume of LAW to be treated. In addition, the timing of implementing the supplemental LAW treatment capacity 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 for this evaluation, as the most current available System Plan, to allow an assessment of the feasibility of each technology under consideration. An assessment using this feed composition is assumed to allow a consistent evaluation of the feasibility of each technology and to enable a cost analysis.

A feed vector (feed volume and composition over time) was provided by Washington River Protection Solutions, LLC (WRPS) that includes monthly average volumes and compositions for the expected feed to the supplemental LAW treatment facility. This feed was adjusted to remove strontium, as 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. Table 1.3-1 and Table 1.3-2 show the feed compositions for major chemical and radiological components, and Figure 1.3-2 shows the expected variations in volume. 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. Additional details for the feed vector are described in Volume II, Appendix B.

[3] The LEFT/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 is disposed of in the State Approved Land Disposal Site (SALDS) at Hanford, while extracted contaminants are captured in a brine solution that is concentrated via evaporation then grouted for disposal at IDF. Effluents sent to LERF/ETF must meet the facility waste acceptance criteria. The treatment capacity of LERF/ETF may not be sufficient for all options considered.

Table 1.3-1. Chemical Species in Pretreated Low-Activity Waste

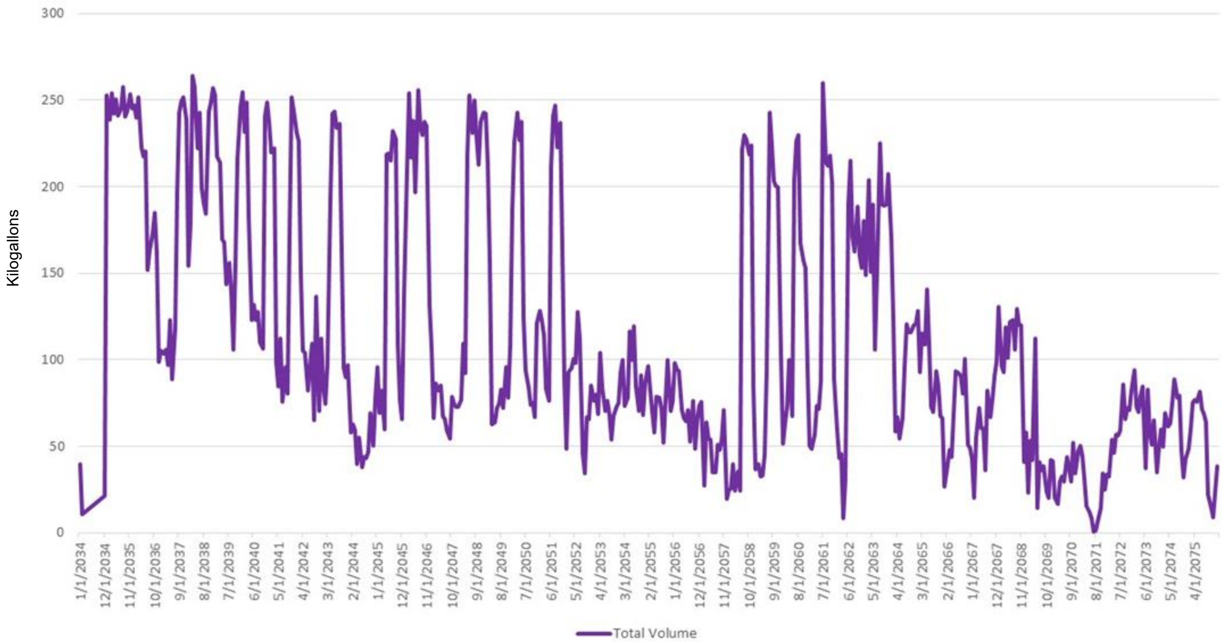
Analyte	Average	Maximum	Minimum	Units
Sodium	159	183	121	g/L
Nitrate	106	195	29.5	g/L
Free Hydroxide	48.8	87.9	7.59	g/L
Nitrite	28.4	64.0	6.27	g/L
Carbonate	17.3	45.2	3.21	g/L
Aluminum	11.1	25.9	1.26	g/L
TOC	5.29	78.45	0.49	g/L
Fluorine	3.56	14.09	0.10	g/L
Phosphate	3.28	12.82	0.24	g/L
Oxalate	3.12	13.77	0.34	g/L
Sulfur	2.78	8.60	0.81	g/L
Chlorine	1.66	4.24	0.46	g/L
Potassium	1.23	6.53	0.17	g/L
Silicon	0.66	3.66	0.05	g/L

TOC = total organic carbon.

Table 1.3-2. Radionuclides in Pretreated Low-Activity Waste Specified for Supplemental Treatment in System Plan 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	301,560	301,566	^{238}U	5.29	5.29
^{151}Sm	50,913	50,913	^{242}Cm	4.59	4.59
^{99}Tc	12,000	12,000	^{237}Np	4.36	4.36
^{63}Ni	5,930	5,930	^{244}Cm	3.31	3.31
^{137}Cs	1,533	1,533	^{60}Co	2.17	2.17
^{241}Am	1,322	1,322	^{152}Eu	2.10	2.10
^{93}Zr	463.8	464	^{155}Eu	1.98	1.98
^{93m}Nb	458.6	459	^{243}Am	0.633	0.633
^{14}C	346.3	346	^{231}Pa	0.482	0.482
^{239}Pu	330.2	330.2	^{227}Ac	0.322	0.322
^{79}Se	222.5	223	^{125}Sb	0.243	0.243
^{59}Ni	106.7	107	^{243}Cm	0.243	0.243
^{126}Sn	95.1	95	^{235}U	0.220	0.220
^{113m}Cd	89.3	89	^{236}U	0.135	0.135
^{241}Pu	88.1	88.1	^{232}U	0.128	0.128
^{240}Pu	67.8	67.8	^{228}Ra	0.047	0.047
^{3}H	48.1	48	^{232}Th	0.039	0.039
^{154}Eu	26.1	26	^{242}Pu	0.031	0.031
^{233}U	15.0	15	^{229}Th	0.027	0.027
^{129}I	12.2	12	^{226}Ra	0.0015	0.0015

[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.



Reference: 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)

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, the 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.

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. 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.

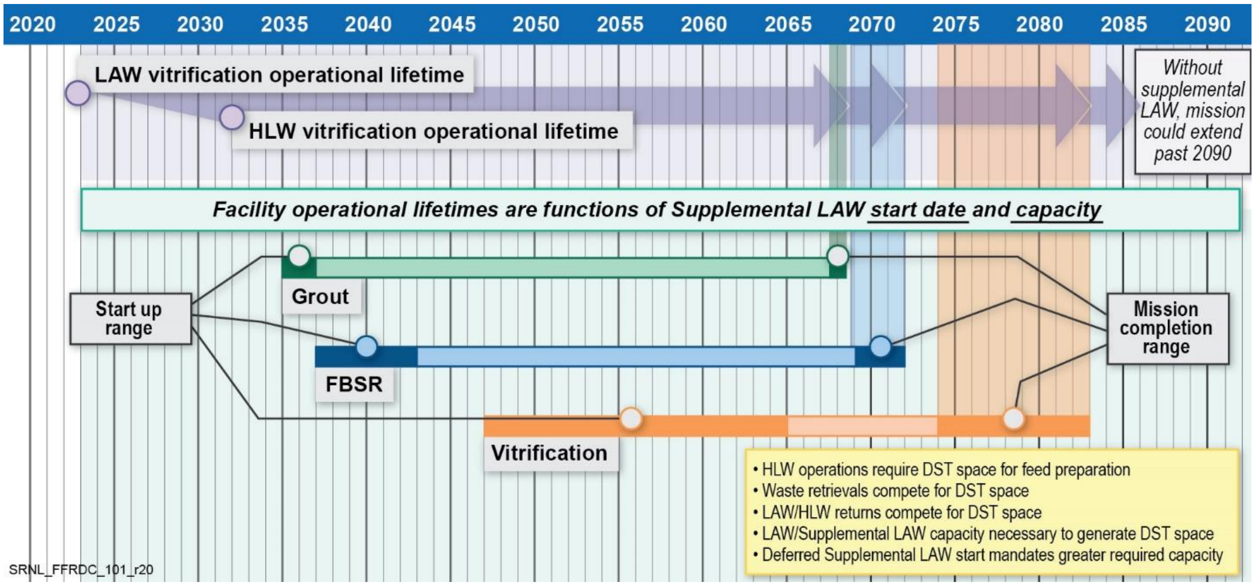


Figure 1.3-3. Relationship Between Low-Activity Waste Supplemental Treatment Start Date and Projected Tank Waste Mission Completion Date

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 – the very volume that 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 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.

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 back to the overall mission (MR-50713, *Model Scenario Request Form for FFRDC NDAA LAWST Modeling*). 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, earlier than 2035 start dates would allow use of available DST space for feed preparation (LAW and HLW) and to support retrievals.[4]

[4] Volume II, Appendix C provides a discussion of 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).

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. In addition, the Hanford Site has extensive surveillance and monitoring protocols and other tank integrity programs to monitor the status of the tanks and reduce the risk of future leaks; these programs are not described here.

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, 750, or 1,000 kilogallon capacity,[5] 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. One of the oldest DSTs 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	Type	Quadrant	Assumed or Confirmed Past Leakers	Comments
T	1943-1944	16	SST	NW	7	
TX	1947-1948	18	SST	NW	8	
TY	1951-1952	6	SST	NW	5	
B	1943-1944	16	SST	NE	10	
BX	1946-1947	12	SST	NE	5	
BY	1948-1949	12	SST	NE	5	
C	1943-1944	16	SST	SE	7	Retrieval complete – awaiting closure
U	1943-1944	16	SST	SW	4	
S	1950-1951	12	SST	SW	1	
SX	1953-1955	12	SST	SW	10	Tank S-122 retrieval complete
SY	1974-1976	3	DST	SW	0	
A	1953-1955	6	SST	SE	3	
AX	1963-1965	4	SST	SE	2	Retrievals in progress
AY	1968-1970	2	DST	SE	1[a]	(Tank retrieved, awaiting closure)

[5] 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.

Table 1.3-3. Hanford Tank Farms

Farm	Years built	Number of tanks	Type	Quadrant	Assumed or Confirmed Past Leakers	Comments
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 December 31, 2022*, Rev. 408, 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.

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 supernatant liquid waste, including drainable interstitial 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.[6] 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: HDWModel 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 in these tanks. However, these measures have not completely removed the potential for future leaks from the ingress of precipitation. 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.

[6] 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 2005.

Retrieval operations to remove waste from a tank typically consist of sluicing the waste with water 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.

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 is 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 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 treated supernatant liquid from the TSCR system for staging feed to LAW vitrification during direct-feed low-activity waste (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 and would delay the DFLAW program much longer than a leak in other DSTs and 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. 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 WTP project and is part of the existing risk registers.

The failure of Tank AY-102 was attributed to pitting corrosion resulting from reactions with chemicals in the tank waste (Follett 2018). In response, the DOE Office of River Protection (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 not described in this report.

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 assessed 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").[7]

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, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*),[8] and considered additional reports and publications related to Hanford supplemental 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) in a recent report on Hanford tank waste summarizes how each of these elements of the legal framework applies to Hanford LAW requiring supplemental treatment (reference pending):

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

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

[8] Discussion of regulatory issues addressed in SRNL-RP-2018-00687 (Section 2.5, page 30) is provided 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 State of Washington 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 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.

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. 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.[9] 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.[10] 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).

[9] 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.

[10] "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).

Ecology has supported the initial phases of a DOE pilot research and development (R&D) program at Hanford, the Test Bed Initiative (TBI).[11] In the TBI pilot completed to date, Ecology supported off-site commercial grout treatment and disposal at a licensed out-of-state commercial land disposal facility, with respect to a small quantity (3 gallons) 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.[12] The LAW used in the 3-gallon TBI demonstration was grouted in Washington State at the Perma-Fix Northwest, Inc. (Perma-Fix) 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, *Nuclear Waste Disposal: Actions Needed to Enable DOE Decision That Could Save Tens of Billions of Dollars*).

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,[13] and other regulations, DOE Orders, and guidance under the foregoing.[14] 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).

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[11] 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).

[12] 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).

[13] 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.

[14] 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, the AEA, and the Washington Hazardous Waste Management Act.[15] 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.[16] The TPA Action Plan establishes milestones for DOE completion of remediation tasks agreed to by the parties, including retrieval and disposition of tank wastes.[17] 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.[18]

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.[19]

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[15] 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 70.105 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."

[16] 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.

[17] 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.

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

[19] 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.[20] 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 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

What kind of supplemental treatment 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, using the state's RCRA-equivalent regulations in lieu of EPA's.[21]

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[22] 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 the Department that is authorized to determine whether the radioactive portion of tank waste is HLW – or not-HLW – and that DOE has not done so yet because under DOE O 435.1 it performs such characterizations following treatment of the waste; such treatment has not yet occurred. 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 (reference pending).

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[20] 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.

[21] 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.

[22] 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.[23]

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, 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, which for LAW necessitates special consideration of LDR requirements for specified metals and organic chemicals (40 CFR 268.42(d)).[24]

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-D11]" (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").

[23] 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.

[24] 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 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.[25] 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 lawfully can 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.[26] 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).[27]

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

[25] 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).

[26] 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).

[27] 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, although, mitigation measures may be required for analytes such as technetium, iodine, or nitrate, 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 (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site*). 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.[28]

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.[29] 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).

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), followed by disposal at a commercial disposal facility (Waste Control Specialists in Andrews, Texas) of 3 gallons of Hanford tank waste, was successfully accomplished during the 3-gallon 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" exemption allowing disposal of Hanford tank waste that does not meet LDR standards.[30]

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 of tank waste that is determined to be WIR under the TBI program, although this program has only dispositioned 3 gallons of tank waste to date and is an R&D program separate from treatment of LAW. Ecology has indicated that it would seek enforceable agreements with potential off-site facilities would be needed, 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 sample-and-send methodology, where waste would not be immobilized by grout unless the resulting immobilized waste would meet the waste acceptance criteria of the receiving facility. Furthermore, having more than one option for out-of-state disposal would mitigate the Ecology concerns regarding waste disposition.

[28] 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.

[29] 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.

[30] To obtain a no-migration exemption, 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 exemptions have been granted. In EPA (2021), EPA Region 7 proposed to reissue a "no migration" exemption 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 no migration exemption by EPA. The majority of no migration exemptions 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 be compliant 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 Appendix C.

The FFRDC team developed and evaluated a set of 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. Based on 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 pre-screening review narrowed the set of viable alternatives to 15 alternatives for detailed analysis. A description of the process is included in Volume I, Appendix A, and the detailed analysis is included in Volume II, Appendix D.

Four alternatives that scored highest against all decision-informing criteria within their technology groups have been selected for direct comparison and to represent the most effective and efficient implementation scenarios for each primary treatment technology and to highlight implementation trade-offs and constraints. Two grout-related alternatives are included. The four 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)
- Phased off-site grouting and disposal, then 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 alternatives (Volume II, Appendix F), assuming an annual DOE ORP budget constraint for supplemental LAW treatment activities of $450 million in 2021 dollars. Because the NDAA21 Section 3125 did not provide budget guidance for the analysis, this budget constraint was selected based on comparability to the DFLAW budget. 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. 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 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 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.

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 key 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.

The four key alternatives considered in this evaluation are listed 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.

Table 3.3-1. Brief Title and Description of Key Alternatives

Alternative designation	Alternative title	Brief description	Disposal Location	Secondary Solid Waste Disposal
Vitrification 1	Single Vitrification Plant	Construct additional melter facility	On-site	On-site
FBSR 1A	Fluidized Bed Steam Reforming – On-site Disposal	Construct FBSR facility; dispose monolith waste form onsite	On-site	On-site
Grout 4B	Off-site Vendor for Grouting – Off-site Disposal	Ship liquid to off-site vendor for grouting; dispose containerized grout offsite	Off-site	Off-site
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	Off-site and On-site	Off-site and On-site

FBSR = fluidized bed steam reforming.

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. Additional comparisons of the four alternatives are provided in Volume I, Appendix B.

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.

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 ^{90}Sr and some actinides as an added benefit by using CST.[31]

The simplified schematic of the TFPT process is shown in Figure 3.3-1. 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 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 columns from TFPT are interim-stored onsite, with the expectation that the media will eventually be vitrified at the WTP HLW Vitrification Facility.

[31] 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.

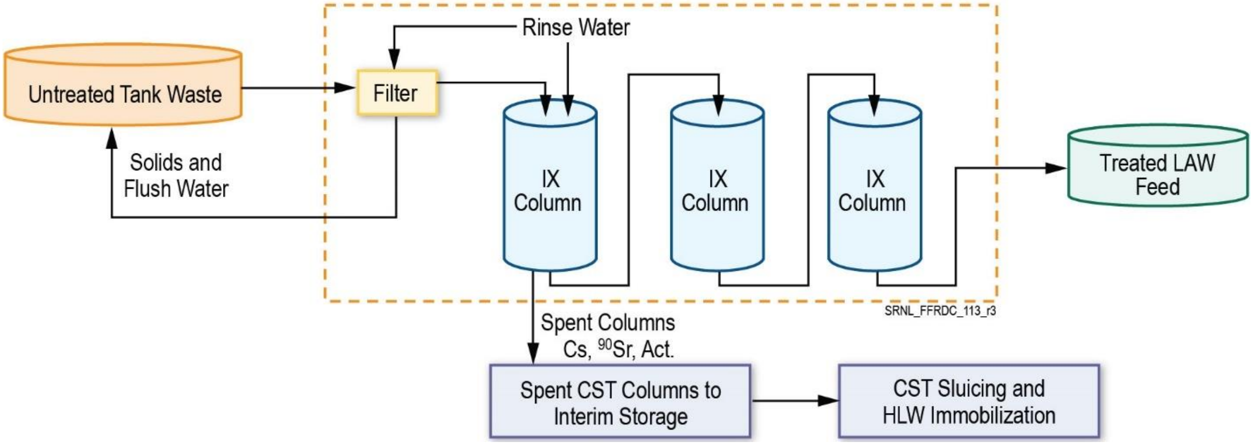

Figure 3.3-1. Tank Farms Pretreatment Process

The extent of removal of ^{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. 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 ^{90}Sr is approximately 10 times greater than for cesium 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 ^{90}Sr was removed.

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[32]). 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 (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*).

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).

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

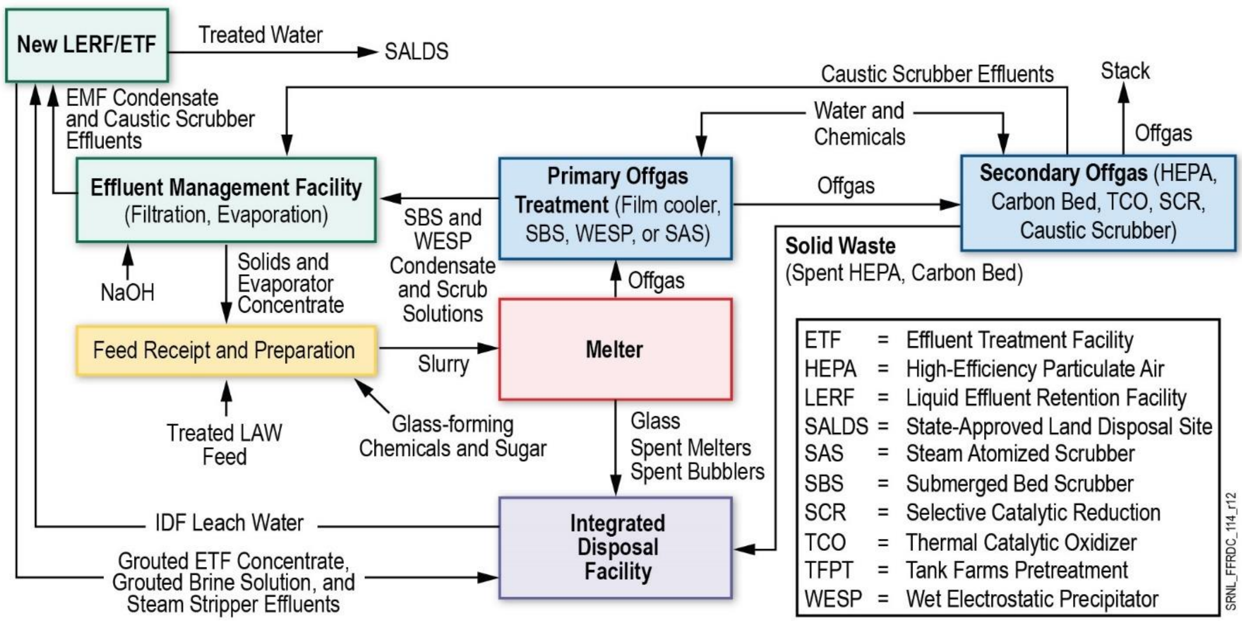

Figure 3.3-2. Flow Diagram of Vitrification

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 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. 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 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. This concentrated stream will be grouted and sent to the IDF for disposal. Effluents from the steam stripping process will be sent to an off-site vendor, grouted, and disposed in the IDF. As documented in RPP-RPT-60974, *ETF New Waste Stream Acceptance Package for WTP Effluent Management Facility*, this stream is expected to be suitable for disposal in IDF.

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, encapsulated in grout, and disposed of in the IDF along with the immobilized waste from the ETF.

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.

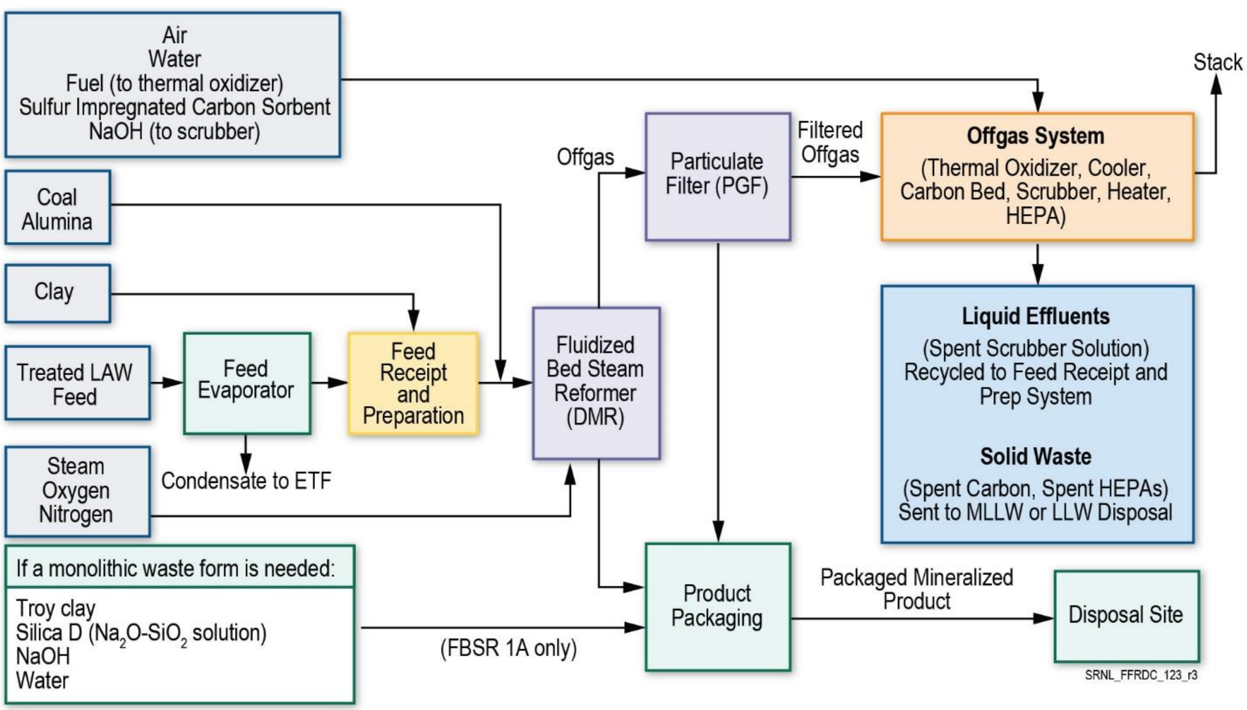

Figure 3.3-3. FBSR 1A, Fluidized Bed Steam Reforming with On-site Disposal

A geopolymer process downstream of the FBSR converts the granular FBSR product to a monolith, which is needed to meet the IDF 85 lb/in.^{2} compressive strength limit required for IDF disposal. That step is shown as part of product packaging 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 granular FBSR product is mixed with clay, silica, caustic, and water, poured into containers, cured, and disposed of.

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[33] 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 (e.g., zero potable water pathway), 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.

This alternative uses an off-site vendor to immobilize the treated supernatant liquid. 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.[34] 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 8.4 m^3 steel frames, each with a heavy-duty polypropylene bag liner. The grouted waste, compliant with respective facility waste acceptance criteria, is then sent to an off-site facility for disposal (Energy*Solutions* [Clive, Utah] or Waste Control Specialists [Andrews, Texas]). Figure 3.3-4 shows alternatives Grout 4B, including off-site disposal.

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.

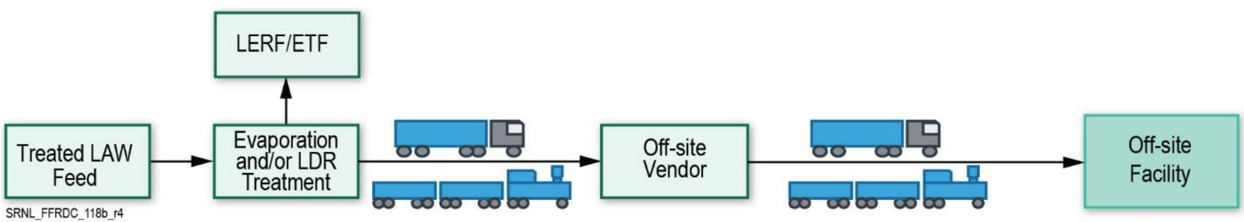

Figure 3.3-4. Flow Diagram for Alternative Grout 4B

In alternative Grout 4B, 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 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.

33 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.

34 The ability to ship pretreated liquid tank waste at a small scale (~3 gallons) was demonstrated during the TBI (DOE/ORP-2019-02, *Test Bed Initiative (TBI) Phase 2 Research, Development, and Demonstration Permit Application*).

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.

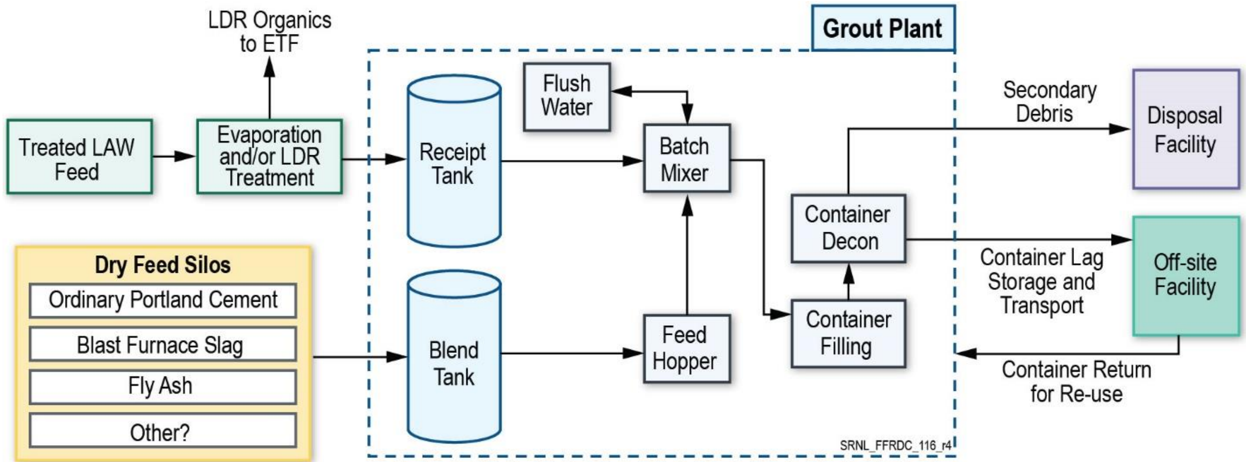

Figure 3.3-5. Typical Containerized Grout Processing Facility

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 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.[35] 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.[36] 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.

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 low-activity liquid waste after pretreatment offsite 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 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 assumed available 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). Any additional funding expended on off-site grouting 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.

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[35] An acceptable method to transfer the diverted waste to the WTP LAW Vitrification Facility is assumed.

[36] Low temperature oxidation was planned for treatment of organics during the initial TBI, but was not needed since organic concentrations were below action limits.

Although there are several potential hybrid alternatives, Alternative Grout 6 was found to dominate the hybrid alternatives. 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 information and modeling needed to complete remaining technology maturation to support the final phase of on-site disposal 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 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.

This alternative is a phased approach that combines alternatives Grout 4B (off-site vendor, off-site disposal) and Grout 2B (separate plants with off-site disposal) in phased startup, and transitions to an on-site disposal method (Volume II, Appendix C provides details on each alternative). The schematic for Grout 4B is the same as that shown in Figure 3.3-4. The schematic for the subsequent phase comparable to Grout 2B is shown in Figure 3.3-6 (on the next page). 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.

The purpose of this alternative is to expedite retrieval and disposal of wastes within site budgetary limits. The hybrid concept of this alternative is to initially pretreat the waste in the 200 West Area in a TFPT system, undergo LDR treatment (if needed), and the liquid is then shipped to an off-site immobilization vendor and the grouted waste form is disposed of offsite (comparable to alternative Grout 4B). A second TFTP and LDR treatment process would be constructed and operated in the 200 East Area, with the same off-site grouting and disposal steps, similar to alternative Grout 4B. This alternative allows 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 and LDR treatment, and the on-site grouting plant creating a waste form that is disposed of onsite, similar to alternative Grout 1A or 5A/B. The exact configuration and operation of the on-site grout production and disposal system (i.e., Grout 1A or 5A/B) would be determined in the interim period.

Since the off-site contractor is initially handling both immobilization and disposal, 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. Figure 3.3-4 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 the WTP HLW Vitrification Facility startup. During the start-up and initial operations of the WTP HLW Vitrification Facility, an on-site grouting capacity will be developed and constructed in the 200 East Area. On-site grouting operations will commence in 2039 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.

Figure 3.3-6, provides a schematic representation of this portion of the alternative, which is comparable to alternative Grout 2B. 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.

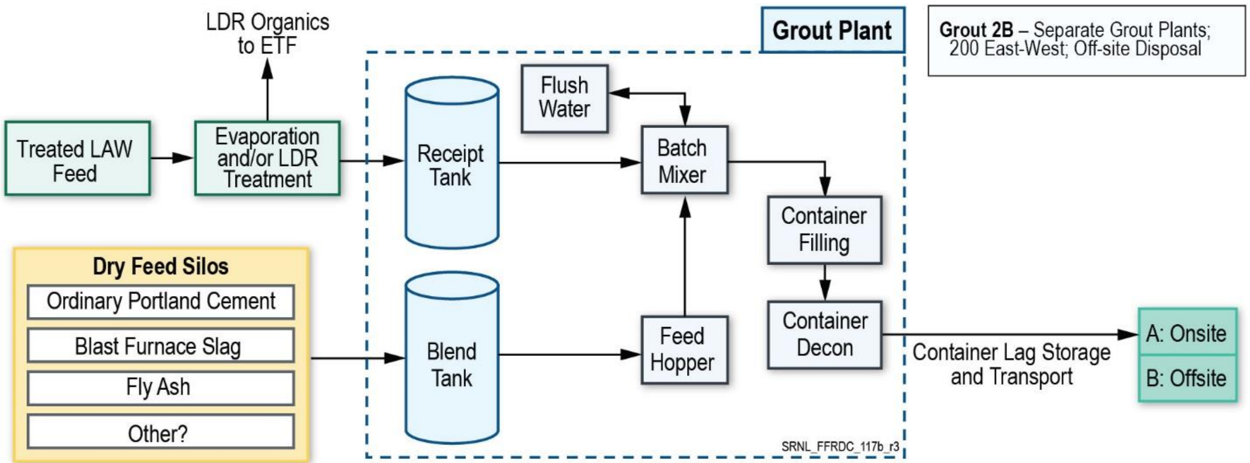


Figure 3.3-6. Schematic of Containerized Grout Production Onsite, with Off-site or On-site Disposal

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 generate LAW feed; the program will be required to process significantly more volume.

The above analysis describes LAW supplemental treatment alternatives per this study. Previous work based on unit operations, and the chemical modeling and associated lifecycle cost modeling tools used for DOE 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 recent study provided an analysis for a mission with LAW supplemental treatment delayed until 2050. This model run, MR-50713, was used to provide a parallel analysis for LAW supplemental treatment based on cost and schedule. This model run, referred to as Delayed LAW Supplemental Vitrification, was performed by the WRPS Mission Integration Analysis organization and provides a wholistic mission (e.g., LAW/ HLW/tank retrievals) view consistent with analyses reported in the ORP System Plans (ORP-11242).

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.[37] 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 4B allows for direct comparison with the Delayed LAW Supplemental Vitrification run results.

[37] One significant difference between this study and the NDAA17 effort is the reporting of cost in constant (assumed 2023 basis), unescalated dollars. This allows the costs to be better reflected against other DOE-led estimates such as in DOE/EIS-0391 (2008 constant dollar basis) or the various ORP System Plans (ORP-11242). Escalated costs are also provided for the mission profile as per standard practice.

Comparisons between the vitrification alternative (Vitrification 1), as developed for this study, with the Delayed LAW Supplemental Vitrification run can be made to illustrate mission and LAW supplemental treatment specific costs.[38] 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.[39]

The key difference regarding the modeling for this effort is processing the 200 East Area excess LAW feed via vitrification starting in 2050 versus the early off-site grout with off-site disposition. The TOPSim results are reflected in a cost/schedule profile reflecting the entire tank waste mission. TOPSim results were compiled along with the Tank Operations Contractor work breakdown structure for the tank waste mission and reflected as a lifecycle cost profile, as shown in Figure 3.3-7 and Figure 3.3-8.

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%).[40] Again, this is primarily due to fewer years of process operations, lower LAW supplemental treatment annual costs, and capital avoidance.

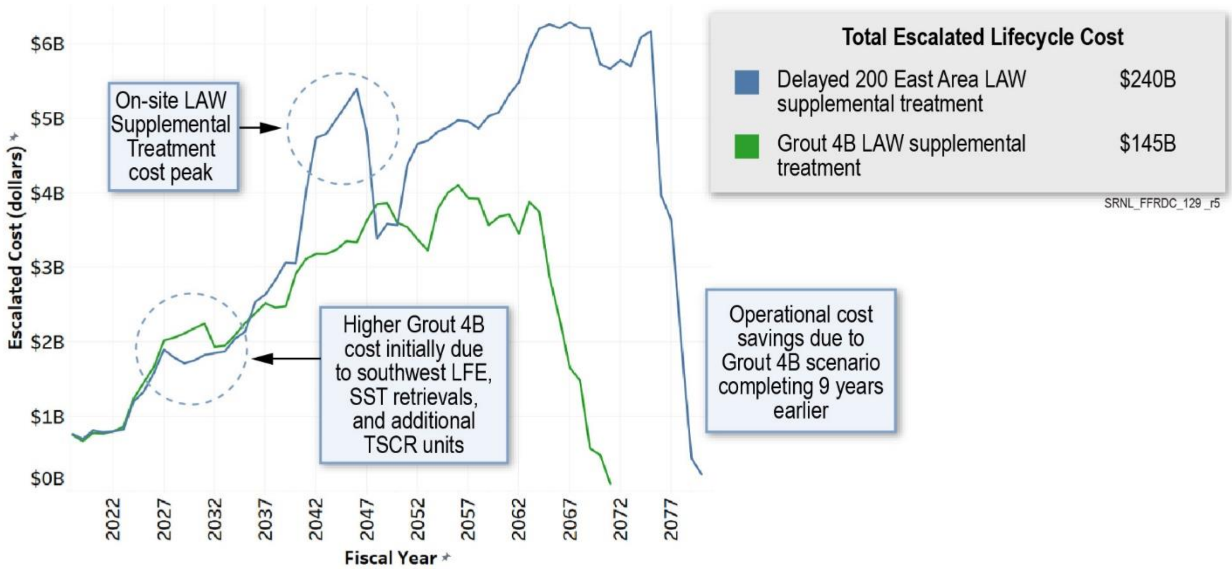
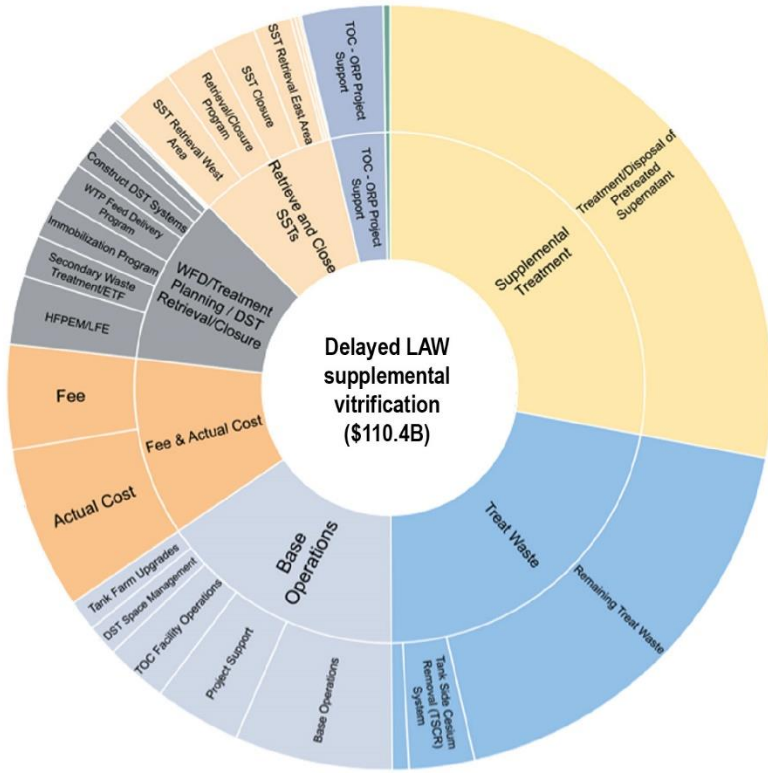


Figure 3.3-7. Annual Mission Cost Profile Comparison between Alternative Grout 4B and Delayed Low-Activity Waste Supplemental Vitrification

Figure 3.3-8 provides a summary, comparative view of costs by work element. These "wheel" diagrams provide perspective on the relative cost of work elements. The single largest element per the vitrification options is LAW supplemental treatment – greater than all of WTP or combined retrieval/closure and waste feed preparation. Note that the wheels are also sized to show the total project cost.

[38] Another significant difference in this modeling effort and the NDAA17 work is that the feed vector reflects feed preparation and pretreatment operations as described in the process logic of the Delayed LAW Supplemental Vitrification study versus the System Plan (ORP-11242, Rev. 9).
[39] The logic provided for the TOPSim model is described in Volume II, Appendix F of this study. Full details – retrieval patterns, feed preparation, transfer logic – are documented in MR-50713.
[40] 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.



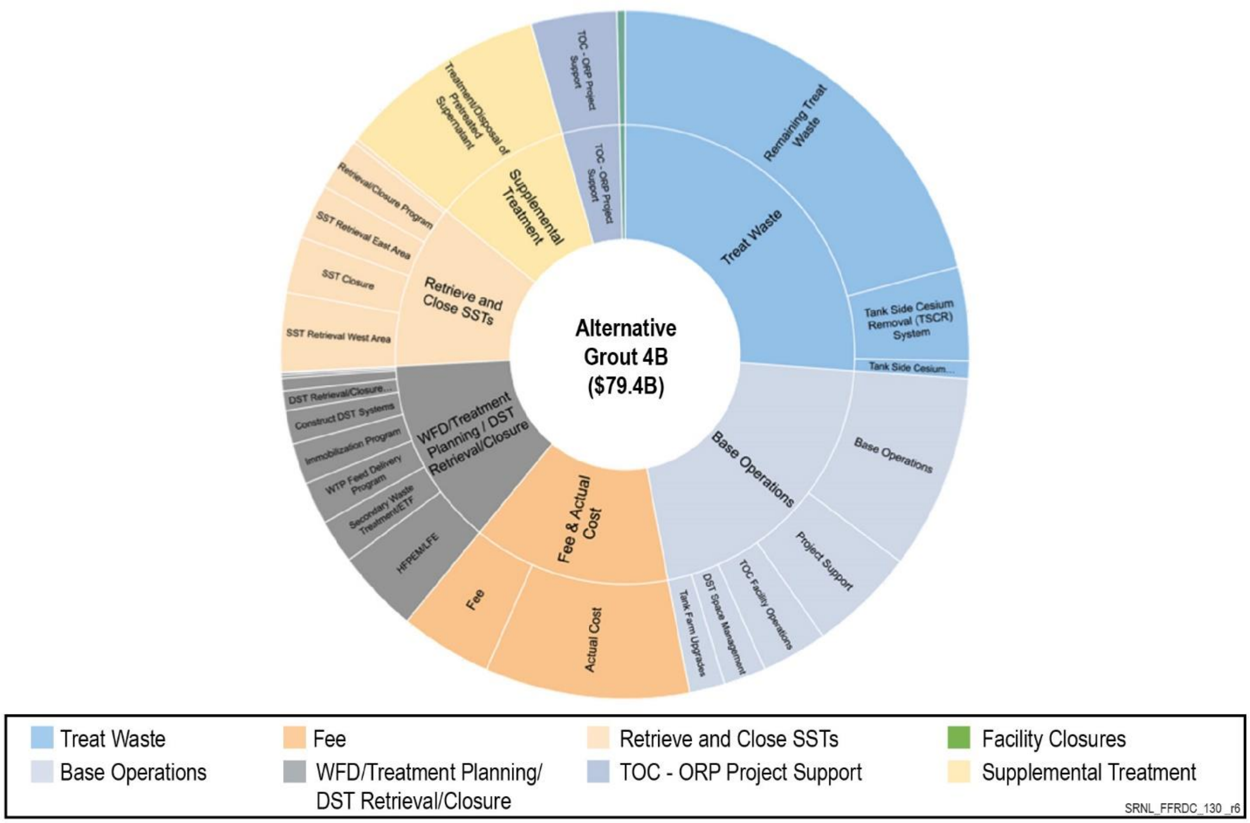


Figure 3.3-8. Cost Elements by Work Breakdown Structure – Alternative Grout 4B and Delayed Low-Activity Waste Supplemental Vitrification

Table 3.3-2 illustrates the impact of LAW supplemental treatment processing on HLW canister production requirements, pretreatment system requirements, and retrieval completion, in addition to mission cost.

Table 3.3-2. Mission Performance and Cost Metrics – Alternative 4B and Delayed Low-Activity Waste Supplemental Vitrification

	Alternative 4B Early Start Offsite Grout	Delayed LAW Supplemental Vitrification (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.

Table 3.3-3 provides an additional view of mission performance. 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 3.3-3. Technetium-99 Disposition – Alternatives 4B and Delayed Low-Activity Waste Supplemental Vitrification

Disposal	Waste Type	Treatment	Alternative 4B Ci Tc	Delayed Vitrification Ci Tc
Offsite	LAW	West TSCR	6,500	7,500
Offsite	LAW	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		Delayed LAW Supplemental Vitrification
18,250	Total offsite (Ci)	8,750
6,800	Total on-site IDF (Ci)	16,300

In summary, for this particular comparison the mission cost reduction – $30 billion (unescalated) or $95 billion (escalated), is allowed specifically by supporting tank farm operations and HLW vitrification. In this manner, on-site disposal of technetium and mission length are simultaneously reduced.

To further the analysis, the system planning TOPSim and lifecycle cost data can be used to evaluate the relative value of the process alternatives. 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 relevant data that can be interpolated to provide comparisons for the remaining alternatives. This type of analysis is similar to that found in recent GAO reports (GAO-17-306, *Opportunities Exist to Reduce Risks and Costs by Evaluating Different Waste Treatment Approaches at Hanford*, and GAO-22-104365) and can be used to compare these types of studies and provide a common reference point for decision makers.

Four process alternatives were selected to represent the scale of relative performance metrics for the following parameters.

- LAW supplemental treatment startup
- Near-term cost and funding requirements
- Process performance: LAW feed volume processed and technetium curies dispositioned
- Alternative cost through end of mission.

The final four process alternatives selected include:

- Vitrification 1 – On-site vitrification facility with IDF disposition
- FBSR 1A – On-site FBSR facility with IDF disposition
- Grout 4B – Off-site grout with off-site disposition
- Grout 6 – Off-site grout/off-site disposition through 2039; on-site grout/grout disposal unit (GDU) disposition 2040 on.

These alternatives were selected to 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. The relationship between incurred cost at the projected performance within the soon-to-start (2023) tank waste clean-up mission for the four alternatives is shown in Table 3.3-4.[41]

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.[42]

To prepare for, construct, and then operate LAW supplemental treatment will require significant funding throughout the mission for all alternatives. The volumetric feed consumed by each alternative will approach or exceed 90 Mgal. However, there is a disproportionate difference between alternatives regarding potential technetium disposition. This is due to the concentration of technetium in the initial LAW feed.

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

[42] 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 Delayed LAW Supplemental Vitrification 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 5A 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.

Table 3.3-4. Comparison of Cost and Projected Performance of Low-Activity Waste Supplemental Treatment Alternatives

LAW Supplemental Treatment Alternative	Cumulative unescalated cost ($M)				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)	2,205	5,605	8,105	23,400 (2075)	-	-	-	83[e]	-	-	-	6,640 (27%)
FBSR 1A (on-site facility with IDF disposition)	1,593	3,523	4,789	8,417 (2070)	-	-	25	86[e]	-	-	5,700	10,210 (41%)
Grout 4B (off-site grout with off-site disposition)	1,319	2,489	3,959	6,449 (2066)	14	34	58	97	6,900	10,100	12,600	15,600 (64%)
Grout 6 (off-site grout with off-site disposition through 2039; on-site facility with GDU disposition 2040 on)	1,434	3,240	3,361	5,039 (2066)	14	34	58	97	6,900	10,100	12,600	15,600 (64%)

[a] Key mission activity: 2033 – Start of HLW vitrification.
[b] Key mission activity: 2039 – Start of FBSR for supplemental LAW.
[c] Key mission activity: 2047 – Start of vitrification for supplemental LAW.
[d] The mission end date varies by treatment technology.
[e] Interpolation between model runs. Gallons processed assumes that all feed not delivered to LAW vitrification is processed via supplemental LAW technology, indicative of scale as a function of mission duration. HLW vitrification will immobilize about 1,250 Ci Tc. LAW vitrification will immobilize (for on-site disposition) 6,800 to 11,900+Ci Tc, depending on mission duration and start of supplemental LAW processing. The tank farms inventory of ≈25,000 Ci Tc implies that all non-HLW immobilized Tc (plus about 1% residual) would be dispositioned onsite as immobilized supplemental LAW with ≈23,500 Ci Tc. The model run provided for supplemental LAW vitrification did include partial off-site disposition (7,500 Ci Tc) so as to allow for accelerated mission completion – 2075 as shown above per Note d.

GDU = grout disposal unit.
HLW = high-level waste.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
MCi = million curies.
Mgal = million gallons.
Tc = technetium.

This feed is currently the supernatant liquid in the DSTs and is significantly enriched in soluble technetium versus the precipitated salt in the SSTs.[43] 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 Delayed LAW Supplemental Vitrification 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. 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 return than any other alternative.

[43] 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.

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.

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 affordability and robustness to technical risks)
4. Lifecycle costs (discounted lifecycle costs).

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. 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; however, implementation of more restrictive requirements by the state of Washington is possible. On-site disposal in the IDF must meet long-term performance requirements for a 1,000-year DOE compliance period, and the IDF performance assessment (RPP-RPT-59958) also evaluates a 10,000-year post-compliance period for sensitivity analysis. For example, the RCRA permit for IDF requires mitigation measures if long-term performance projections indicate that future groundwater concentrations may exceed 75% of the maximum contaminant limit.

Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration) assesses the near-term 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), the overall risk assessment was dominated by risks associated with the ongoing degradation of aging waste storage tanks at Hanford and by the overall duration of activities to empty the waste tanks. Processing flexibility is important in assessing confidence in durations.

Likelihood of successful mission completion (including affordability and robustness to technical 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. There are significant risks of project failure for some alternatives. In addition to assessing technical and engineering risks to project completion, the FFRDC team also assessed affordability, and found it to be the dominant risk to program success. An assumed budget of $450 million/year (additive to current budgets) was used to assess affordability. Sensitivity to this assumption was considered in Volume II, Appendix F.

Lifecycle costs (discounted lifecycle costs) estimate the total cost to implement each alternative within a plausible annual budget. The estimates developed for this study therefore differ from past unconstrained estimates: the affordability 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 used in 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 execution. Operations schedules, which are driven by the outputs of the WTP HLW Vitrification Facility processing, were not allowed to stretch. Instead, any differences between the $450 million/year budget (constant fiscal year [FY] 2023 dollars) and the funds required to process LAW in particular years were calculated and accumulated. Discounted total excess/shortfall under the flat budget are reported for each alternative. Discounting and escalation assumptions are explained in Volume II, Appendix F.

For these four top-tier primary decision-informing criteria, a hierarchical breakout of relevant lower-tier criteria was developed into a criteria taxonomy 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 results 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 with 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:

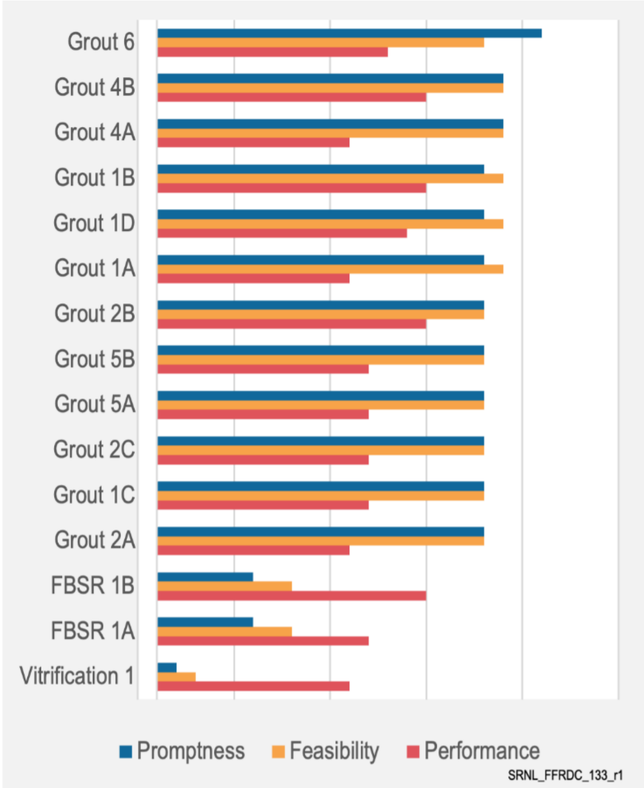
5. Securing and maintaining necessary permits/authorities (regulatory approval)
6. Community/public acceptance.

The FFRDC team assessed the top-level decision-informing criteria, as informed by the taxonomy of criteria the team had developed and adjusted during the course of the elicitation process. In the end, only four to five distinct qualitative levels were assessed for each of Criteria 1 to 3, across the 15 specific alternatives being considered. The team chose text descriptions for how to interpret those levels, and ranked each in order of desirability. The results of that process, and the specific alternatives scored at each level, are shown below.

- **Criterion 1**: Long-term effectiveness (environmental and safety risk after disposal)
  - 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

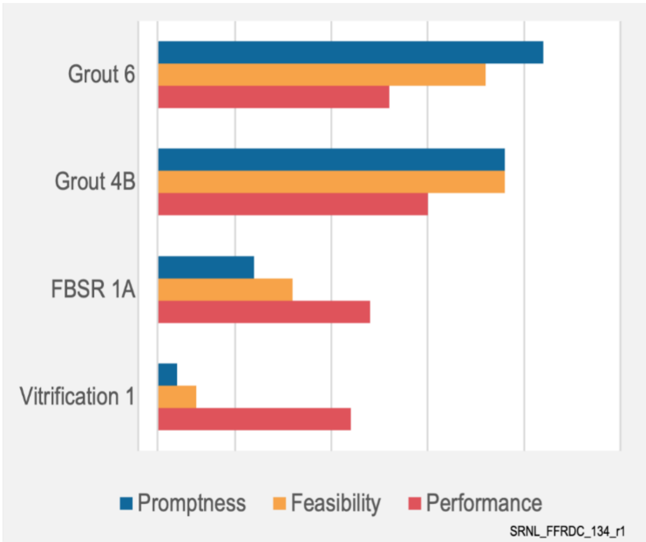
- **Criterion 2**: Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)
  - 2027 operations, 2065 completion, low risk with flexibility (Grout 6)
  - 2027 operations, 2065 completion, moderate risk (Grout 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 1, FBSR 2)
  - 2050 operations, 2075 completion, high risk (schedule) (Vitrification 1)
- **Criterion 3**: Likelihood of successful project completion (including affordability and robustness to technical risks)
  - 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).

Figure 4-1 shows the FFRDC team's assessments of the qualitative decision criteria (Criteria 1 to 3) for all 15 alternatives on a notional scale that reflects the team's subjective assessment of the significance of each assessed score. The details of the underlying assessments are provided in Volume II, Appendix D. Note that most of the grout alternatives score no better in any these criteria than either Grout 6 or Grout 4B.



Performance = Criterion 1, Promptness = Criterion 2, and Feasibility = Criterion 3.

Figure 4-1. Qualitative Alternatives Comparison



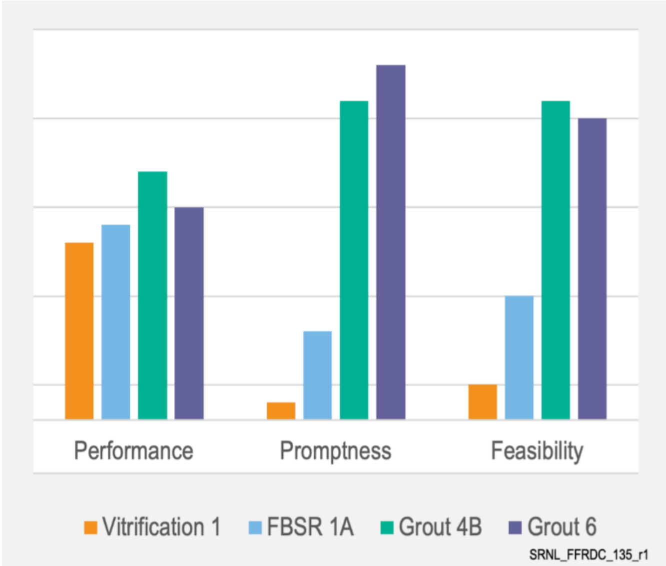
Performance = Criterion 1, Promptness = Criterion 2, and Feasibility = Criterion 3.

Figure 4-2. Qualitative Alternatives Comparison of Four Representative Alternatives

Figure 4-2 shows this comparison for only the four representative alternatives.

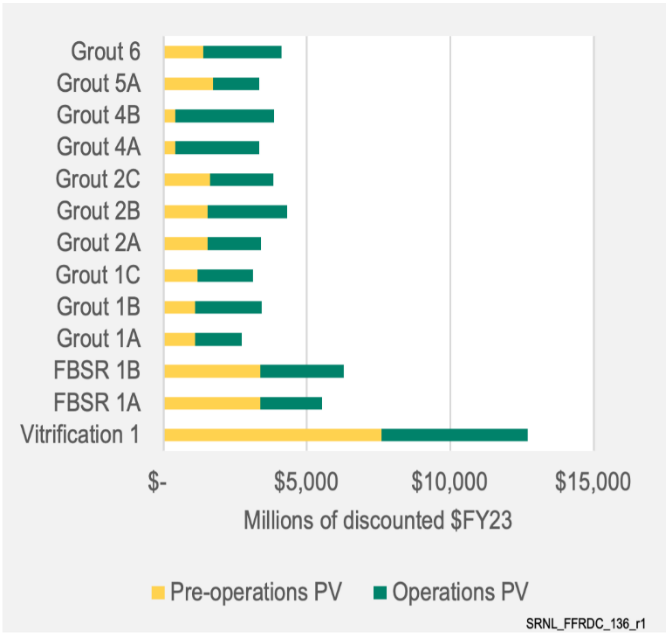
Figure 4-3 shows the assessments of the four representative alternatives grouped by criterion.

For Criterion 4, discounted lifecycle costs were separated into the costs required prior to the beginning of operations and the costs required for operations. Figure 4-4 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.)



Performance = Criterion 1, Promptness = Criterion 2, and Feasibility = Criterion 3.

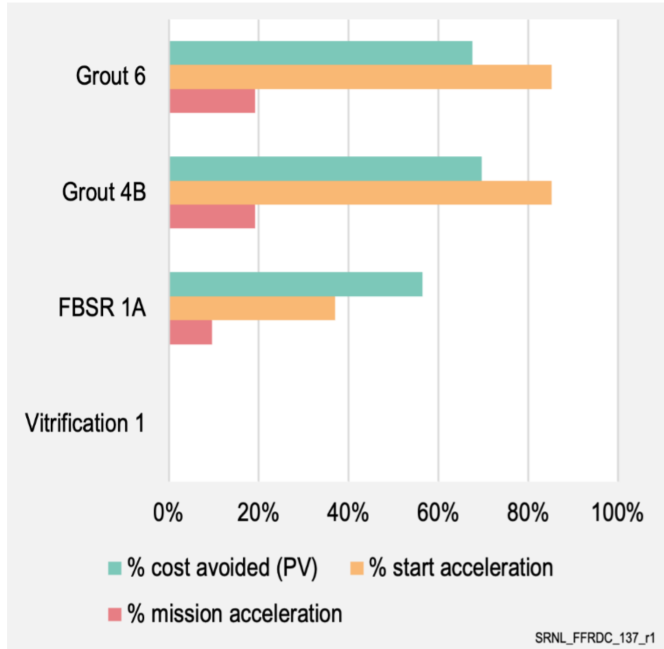
Figure 4-3. Comparison by Criterion



FY = fiscal year, PV = present value.

Figure 4-4. Present Value of Supplemental Treatment Costs

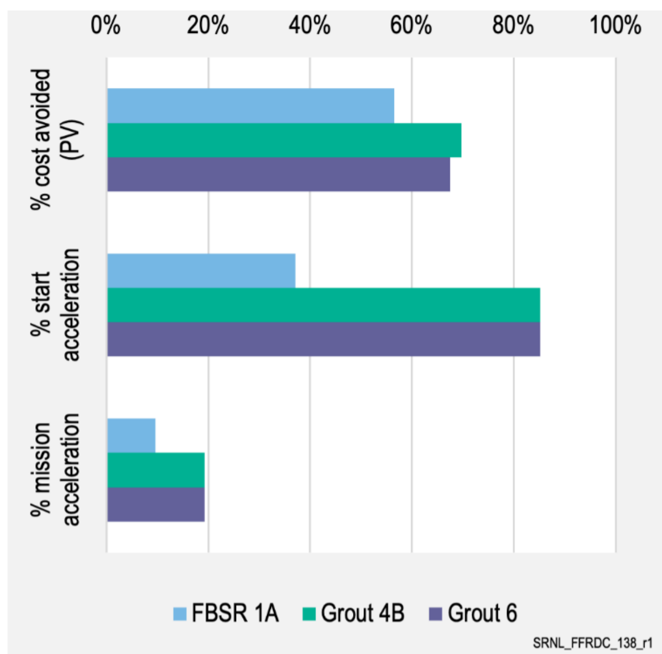
To depict relative cost and schedule desirability of alternatives, the FFRDC team noted that the Vitrification 1 alternative had the greatest cost, the longest delay to beginning treatment of supplemental treatment of LAW, and the latest completion of the treatment mission. Cost and schedule assessments were therefore measured as the costs or duration avoided relative to the Vitrification 1 option. Figure 4-5 shows this comparison in percentage terms for the four representative alternatives. (Vitrification has a score of 0% on each measure.) Figure 4-6 shows this same comparison grouped by criterion. Again, Vitrification1 scores 0% on each criterion by definition.



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 4-5. Quantitative Criteria – 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 4-6. Quantitative Criteria (Grouped by Criterion) – Relative to Alternative Vitrification 1

Figure 4-7 shows the tradeoffs between cost avoidance and time to begin supplemental treatment of LAW among the 15 alternatives.

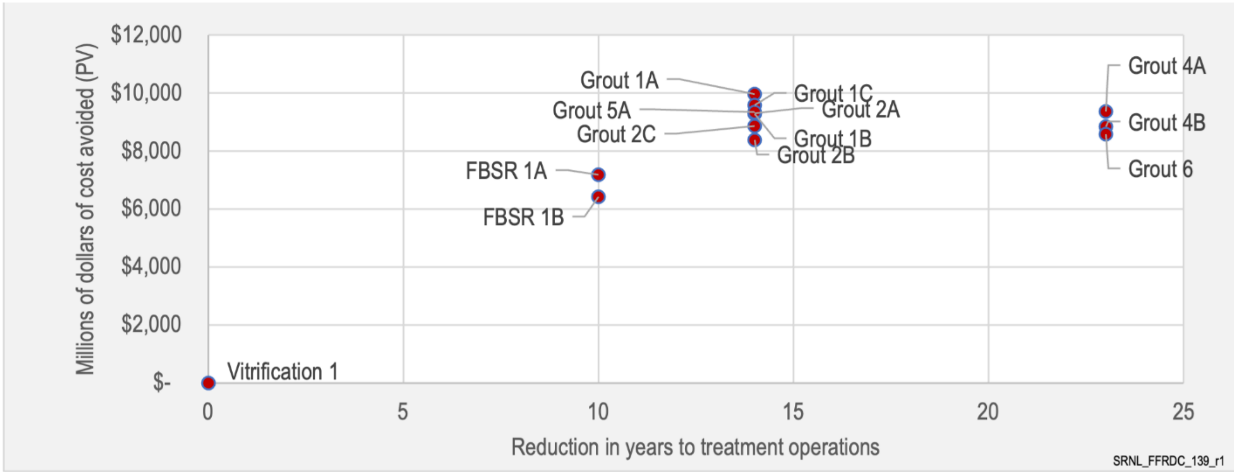


Figure 4-7. Cost Avoidance vs. Schedule Acceleration

Figure 4-8 shows the analogous tradeoffs between cost avoidance and time to complete the RPP mission.

Figure 4-8. Tradeoff of Cost Avoidance vs. Schedule Acceleration

The FFRDC team concluded that stakeholders 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. Instead, they are addressed in discussions of the alternatives.

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 Consolidated 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 implementation and waste tank storage duration)			
High risk due to significant cost-based startup delays and operations limits. Moderate technical implementation risk. Construction finishes 2049, mission does not complete without significant additional annual budget.	High risk due to construction time required and technical execution risk. Construction finishes 2039; mission completes 2070.	Low risk due to immediate start, 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 2065.	Very low risk due to immediate start, flexible timing of conversion to on-site low-temperature process, and inexpensive operations. Grout plant construction finishes 2039; mission completes 2065.
Criterion 3: **Likelihood of successful mission completion** (including affordability and robustness to technical risks)			
Very low probability of successful completion due to affordability.	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 lifecycle costs)			
$7.6B construction; $5.1B operations (unaffordable, $1.36B shortfall)	$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 low likelihood of mission completion because the estimated operating costs significantly exceed the assumed flat annual funding of $450 million, and is therefore unaffordable at this funding level. Vitrification 1 is the only alternative that was found to be unaffordable with this funding case. Capital costs are spread over time as necessary to stay below the annual funding constraint, resulting in a longer duration until the start of operations in 2049. Operational costs cannot be spread over time and the cumulative funding shortfall in 2075, the earliest date that the alternative could complete if adequate funding were available, is $1.36 billion (present value). 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 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 2040 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 outside vendor in 2027 and complete operations in 2065, thus reducing environmental risks related to storage tank degradation 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. Because the first phase of Grout 6 results in a large inventory of technetium and iodine being disposed of offsite, and the grouted secondary waste of Vitrification 1 concentrates radionuclides in a smaller volume than the grout alternatives, Grout 6 is expected to be more effective for long-term performance than Vitrification 1.

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 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. Based on current and anticipated budgets for Hanford, only grout-based disposition alternatives appear to have a realistic chance of being affordable. Escalating costs and inflation only exacerbate the budget challenges. FBSR alternatives are on the verge of affordability but carry first-of-a-kind technical risks for Hanford LAW disposition. Typical levels of cost growth over the course of the project would greatly exceed projectable budgets.

   Vitrification, as the primary supplemental LAW treatment capacity, appears unaffordable under even the most optimistic assumptions – the annual fixed costs of operations, prior to actually processing any waste, are estimated at roughly $500 million/year in current prices and have been escalating faster than general inflation for some time. This assumes continuous full-rate operation without interruption, which is also unlikely.

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 available).

3. The FFRDC team determined that 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.

4. FBSR is considered a first-of-a-kind technology for Hanford LAW and thus, uncertainties in process and waste form performance, cost, and schedule are significantly higher for alternatives using this technology than grouting and vitrification alternatives.

5. Cost is the primary constraint on technology affordability and treatment duration. Alternatives with lower capital expenditures can be implemented earlier and achieve earlier risk reduction through tank waste retrievals, including from assumed and known leaking tanks.

6. Off-site disposal of non-vitrified treated LAW can result in ~50% of the inventory of ^{99}Tc, ^{129}I, and nitrates, respectively, disposed of at licensed LLW facilities outside of the state of Washington, with minimal risks of waste being returned to Hanford. Evaluation of the projected supplemental LAW feed vectors indicates that when grouted ~80–94% of the pretreated LAW will meet NRC technical requirements for Class B or Class A LLW and waste acceptance criteria at NRC-licensed disposal facilities outside of the state of Washington. The FBSR alternative would have ~60% of the waste forms as Class B or Class A. This approach eliminates the concern regarding potential additional impacts to Hanford groundwater and the Columbia River from on-site disposal of non-vitrified LAW.

7. Immobilization of approximately ~50% of the ^{99}Tc and ^{129}I is expected to occur through the DFLAW process, which will operate in parallel with supplemental LAW treatment. DFLAW operations will not be completed when supplemental LAW treatment operations commence; however, a significant inventory of the technetium and iodine will be treated by DFLAW processing.

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 requiring vitrification of HLW states that the intended applicability of the vitrification LDR is only to the high-activity fraction of tank waste determined to be HLW and not to the low-activity fraction (LAW), and further states 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 multiple agencies over commercial MLLW, EPA granted sole authority over treatment, transportation, and disposal to the NRC (reference pending).
9. A decision on the LAW supplemental 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

This recommendation is based on a technical evaluation of multiple alternatives considering long-term effectiveness (environmental and safety risk after disposal), implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration), likelihood of successful mission completion (including affordability and robustness to technical risks), and lifecycle costs (discounted). Alternative Grout 6 most closely provides an example implementation scenario of the recommendation; however, a range of possible implementation scenarios exists. 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 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.
  - 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.
- 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.
- May reduce or eliminate the need for future additional treatment capability and affords time to make such decisions.
- Minimizes financial demands by most closely aligning with the annual planning budget and reducing mission duration and lifecycle costs.
- Most likely to be successfully implemented.

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 accepted, regulatory and stakeholder elements of the recommendation 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.

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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 CONSOLIDATION OF CRITERIA

A.2.1 Specification of Primary Decision-Informing Criteria

To provide the most useful information to decision-makers, the FFRDC team thought it important to distinguish means from ends, and to clearly separate (to the degree possible) the characteristics of individual supplemental LAW treatment alternatives that determine their desirability. To do this, the team took as their model the decision-informing criteria established in the *Resource Conservation and Recovery Act of 1976* (RCRA) and *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA). Taken together, these statutes establish preliminary primary top-tier criteria for assessing proposed public expenditures for environmental remediation in these terms, which the team tailored for suitability to the supplemental treatment of Hanford LAW:

- Long-term effectiveness (environmental and safety risk after disposal)
- Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)
- Likelihood of successful mission completion (including affordability and robustness to technical risks)
- Lifecycle costs (discounted lifecycle costs)
- Securing and maintaining necessary permits/authorities (regulatory approval)
- Community/public acceptance.

The following provides an explanation of these top-tier criteria:

1. **Long-term effectiveness** (environmental and safety risk after disposal). The intent of remediation activities is to permanently solve the problem posed by the contamination to be remediated. Long-term effectiveness considers the extent to which the proposed action would actually solve the problem. This is a combination of the degree to which the action is expected to remediate the current situation, and the justified level of confidence in this projection. For the supplemental treatment of LAW at Hanford, long-term effectiveness consists of immobilizing the contaminants in the LAW away from any potential contamination of human-use water or natural ecosystems at one or more final disposition sites. This criterion does not address risks during supplemental LAW processing; it considers the end state that results when processing is complete, for all primary and secondary waste streams.
2. **Implementation schedule and risk** (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration). Waste disposition activities at Hanford are expected to continue for many decades. This criterion accounts for differences across the proposed alternatives in hazards to people and the environment. This includes not only direct hazards such as worker safety and potential for contamination during processing, but also urgent indirect risks such as the potential for storage tank leakage due to delays in processing. The criterion also accounts for the intrinsic value of earlier completion of processing activities and any differences among alternatives in their potential to delay primary HLW operations at Hanford.

   The formulation of this criterion reflects the FFRDC team's conclusion that schedule duration, while often treated as a primary decision-informing criterion in the analysis of alternatives, is primarily important in the context of supplemental LAW processing for its impact on other risks and costs.

3. **Likelihood of successful mission completion** (including affordability and robustness to technical risks). Not all projects finish successfully. Historically, a number of DOE major projects have not been completed as intended, but have instead been canceled, or rebaselined with a different scope, often with attendant cost increases and delays. This criterion assesses the likelihood that each proposed alternative could be successfully completed as defined. That assessment considers affordability of the alternative, technical and engineering risks of the alternative, and projected availability of critical services and materials. Affordability is assessed in the context of an assumed flat (in constant dollars) budget of $450 million per year for design, construction, commissioning, and subsequent operations.
4. **Lifecycle costs** (discounted lifecycle costs). This criterion assesses the opportunity cost to the nation of choosing a particular alternative. This cost is measured by the estimated discounted constant dollar lifecycle cost to implement the alternative if successfully completed. The details of the assumptions made regarding escalation and discount rates are provided in Volume II, Appendix F.
5. **Securing and maintaining necessary permits/authorities** (regulatory approval).
6. **Community/public acceptance**.

Using these six primary criteria, the FFRDC team constructed a hierarchical taxonomy of supporting lower-tier criteria. The full taxonomy is shown in Attachment A-1. The team then performed a detailed assessment of the first four criteria, based on the best available technical analyses and cost estimates.

For top-tier criteria 5 and 6, the FFRDC team concluded that stakeholders should have the benefit of this and other analyses (e.g., by the National Academies of Sciences, Engineering, and Medicine [NASEM], U.S. Government Accountability Office [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. Instead, the criteria are addressed in discussions of the alternatives.

A.2.2 Assessment and Rollup of Criteria

This section summarizes how the high-level criteria listed above were derived from lower-level assessments specific to the technologies and logistical requirements of the proposed alternatives. The full details of this roll-up from detailed technical findings to qualitative assessments of Criteria 1-4 are provided in the individual selection criteria assessments for each alternative in Volume II, Appendix D.

A.2.2.1 Criterion 1: Long-Term Effectiveness

The FFRDC team assessed long-term effectiveness of each alternative using criteria similar to those specified by RCRA and CERCLA. At the highest level, the team assessed the expected residual threat to the environment and to human health after successful completion of the mission, and the degree of confidence in that assessment. The residual threat was characterized by the extent to which toxicity and mobility of relevant contaminants were reduced. The materials considered for toxicity were RCRA metals, Land Disposal Restrictions (LDR) organics, ammonia, nitrates/nitrites, and greenhouse gases. For mobility, the team also assessed radionuclides (iodine, technetium, and selenium). Cesium and strontium were not assessed for long-term mobility, due to their short half-lives. Health and environmental risks due to cesium and strontium were instead assessed in the context of Criterion 2, Implementation Schedule and Risk.

Mobility of wastes was found to be the primary driver of long-term residual risk, given that there are no significant differences among alternatives in the residual toxicity of the wastes being disposed of. Similarly, since there were no significant differences in expected long-term greenhouse gas emissions across the range of alternatives considered, that criterion was dropped from the analysis.

Confidence in the assessed residual mobility of wastes was based on comparing the error bars in the time-phased mobility point estimates against the amount by which each alternative was predicted to exceed current health standards for each contaminant. These assessments were both contaminant-specific and location-specific, taking into account the geology of the proposed disposal site(s) for the alternative. The top-level assessment of long-term effectiveness incorporates both the estimated performance and the confidence in that estimate.

A.2.2.2 Criterion 2: Implementation Duration and Risk

The magnitude of temporary and near-term risks for each alternative were also assessed by the FFRDC team. Where Criterion 1 was concerned only with the end-state of waste processing operations, this criterion was concerned only with opportunities, hazards, and uncertainties associated with completing the mission, which were divided into four main categories:

1. Risks related to the ongoing degradation of waste storage tank integrity
2. Other risks to human health and safety
3. Other risks to the environment
4. Other consequences of delay in mission completion.

The specific detailed hazard categories considered by the team are shown in Attachment A-1. Because each alternative was designed on the assumption of standard safety and environmental protection practices during construction and operations, the differences among alternatives with regard to workforce health and safety were minimal. Similarly, there were only relatively minor differences among alternatives with regard to environmental risk, with these mostly driven by transportation and handling risks. The dominant factors in assessing overall risk prior to mission completion were thus the hazards associated with tank leakage and the potential impact of supplemental LAW processing delays on accomplishment of the primary HLW mission.

A.2.2.3 Criterion 3: Probability of Successful Mission Completion

It is important for decision-makers to understand when there are significant differences in the probability of successful execution among competing approaches. In assessing the various alternative technologies and disposal locations available for supplemental LAW treatment and disposal, the FFRDC team considered three potential causes for failure to complete the mission:

1. Failure to complete due to technical or engineering challenges
2. Failure to complete due to funding shortfalls
3. Failure to complete due to unavailability of key products, services, or materials.

Technical and engineering risk was assessed by identifying, for each alternative, the most likely technical failure modes and their combined potential to bring the project to a halt. Affordability risk was assessed by establishing a baseline flat annual budget derived from DFLAW cost estimates. Annual construction costs were constrained to stay within this budget on average,[1] and operations costs were compared (but not constrained) against this flat budget. Each alternative was then assessed qualitatively for its affordability, also taking into account the possibilities of growth in cost estimates or escalation rates higher than historical norms. Dependence on external supplies of goods and services was found not to be a significant factor across the range of alternatives considered.

[1] More precisely, flat annual funding at $450 million (FY 2023) was established from 2025 onward, with alternatives permitted to carry forward any unused funds to use in future years. Construction expenditures were limited by cumulative funding at this rate. Construction was assumed to require a minimum of 3 years, regardless of available funding. Annual operations funds were unconstrained, but the cumulative funding deficits (if any) relative to the $450 million budget were included in the total costs for each alternative.

A.2.2.4 Criterion 4: Lifecycle Cost

Distinct from considerations of affordability risk, federal guidance also requires consideration of the indirect impact of public expenditures in terms of the value of other ways those funds could have been spent. This indirect impact is referred to as “opportunity cost”, and the guidance specifies that it be measured using discounted expenditures over time. The FFRDC team computed the discounted constant-dollar cost of each alternative, based on the projected annual expenditures associated with the alternative if executed successfully. Details of the assumptions made about escalation rates, inflation, and discount rates are provided in Volume II, Appendix F, which also discusses the sensitivity analysis conducted with respect to cost and schedule assumptions.

The dominant components of lifecycle cost were the design and construction costs (for those alternatives that involve facilities construction) and the annual operating costs of supplemental treatment of LAW. While construction schedules were constrained by funding and therefore varied in terms of when processing could start, operations schedules were taken to be fixed by the requirements of the overall mission once processing had begun. Supplemental treatment operations are assumed to be capable of meeting throughput demands from the integration into the tank waste mission. It is recognized that this approach underestimates the potential negative consequences of both constrained construction funds and operational funding shortfalls on mission completion.

Shutdown and decommissioning costs were originally included in the taxonomy of cost criteria, but were found to be insignificant. When discounting is applied, the magnitude of these costs is less than the margin of error of the point estimates for construction costs and operating costs, and there are no significant technical or regulatory differences among the various alternatives with regard to shutdown or decommissioning. For these reasons, the FFRDC team did not develop detailed cost estimates for shutdown and decommissioning and did not assess those costs in the reported evaluations of Criterion 4.

The FFRDC team recognizes that cost and schedule estimates over long time horizons are inherently uncertain. At the same time, the team felt that anticipated cost and schedule differences among the alternatives are better conveyed by comparison of point estimates than by an attempt to develop and portray ranges or probability distributions for each alternative. The robustness of the cost findings was assessed through sensitivity analysis on both the overall estimating error (-10% versus +100%) and on the assumed capital project escalation rate (8% versus 4%) for each alternative. The overall conclusions of the report were not sensitive to changes in the estimating assumptions.

A.3 REFERENCES

Comprehensive Environmental Response, Compensation, and Liability Act of 1980, 42 USC 9601, et seq.

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

Attachment A-1– Decision Informing Criteria Taxonomy

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 will be fully evaluated in the Report. 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 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
MOEs: estimated concentration over ~1K years (to DOE O 435.1); delay to peak is when peak occurs and differs between scenarios; identify peak to 10K years for information only (i.e., compliance vs. post-compliance periods)

1.1.2.1.1. Iodine

1.1.2.1.2. ^{99}Tc

1.1.2.1.3. ^{79}Se

1.1.2.1.4. Cesium and Strontium
[Cs and Sr 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 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
MOEs: 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. Selenium-79

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. **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

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
MOEs: 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 (onsite) spills

2.3.4. Offsite 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 affordability and robustness to technical 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: TRLs for CTEs
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. constrained budget

3.2.2. MOE: Projected peak spending vs. constrained 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 lifecycle costs)

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**

6.1. State, Local, and Tribal government acceptance (non-regulatory)

6.2. Community and public acceptance

With respect to criteria 5 and 6, the FFRDC team concluded that stakeholders 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 are not assessed at the top level or included in the roll up with the other criteria. Instead, they are addressed in discussions of the alternatives.

Appendix B. Summary of Selection Criteria Data for Four Key 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-colored descriptors indicate a positive attribute of that alternative, the red-colored descriptors indicate a negative attribute of the alternative. The few brown-colored 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 at IDF in a grout waste form and its long-term behavior is not well understood. I-129 is volatile and its partitioning to the secondary streams and performance in secondary wastes after disposal in IDF are not well understood. There is low mobility of radionuclides and hazardous metals in the cooled glass wasteform with respect to groundwater.
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste is small. Total volume of secondary liquid is large; likely requiring expansion of ETP.
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 RCRA metals (except Hg) are mostly retained in glass wasteform by recycling the offgas condensate.

Alternative Vitrification 1		
	1.2.2 Confidence in immobilization with regard to groundwater	Low confidence in I-129 speciation/partitioning/retention in secondary wastes. High confidence in Tc partitioning during operations and retention in glass. Uncertainty of Tc-99 behavior during melter idling where it extensively vaporizes and distributes to the offgas system components. High confidence in low groundwater impact of I-129 or Tc-99 because of low rate of water available for transport to the groundwater from disposed primary or secondary waste in IDF. High confidence in nitrate/nitrite destruction. Low confidence in ammonia behavior in grouted secondary waste. Leaching of all COCs is mitigated by minimal transport of rainfall thru vadose zone, minimizing mobilization of contaminants to the groundwater.
	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 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 future leaks. Consumption of entire budget will 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 rads 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. 2 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 ETP. I-129 fate in offgas and secondary wastes is unconfirmed.
	2.3.2 Atmospheric discharges	High atmospheric discharges (38 MT COPCs per 1E6 gallons of waste treated)
	2.3.3 Transfer/process tank (onsite) spills	Low onsite and offsite transportation spills
	2.3.4 Offsite transportation spills	Negligible
	2.3.5 Secondary waste streams generated	High quantity of secondary waste streams generated
	2.3.6 Greenhouse gas emissions	High greenhouse gas emissions (3E6 gal fuel, 74 GWh electricity, and 500 deliveries per 1E6 gallons 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 LAW melters. High risk of delay due to annual operating costs exceeding budget.
3 Likelihood of successful mission completion (including affordability and robustness to technical risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Low likelihood of failure – 1st LAW melters will inform design/operations. Low risk of failure to corrosion, fire, release of rads, control of 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 WTP LAW melters will inform design/operations.
	3.1.2 Robustness to known technical risks	Robustness/adaptability – 1st LAW will inform design and operations, mitigating risk by the time the SLAW melters begin operations.
	3.1.3 Adaptability to a range of waste compositions	Ability to adjust waste loading and GFC recipe will 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 will likely exceed the annual spending constraints.
	3.2.2 Projected peak spending	Peak funding needs will likely greatly exceed the annual spending constraints.
	3.2.3 Schedule flexibility	Low schedule flexibility; melters have limited ability to operate at varying rates due to cold cap coverage.
	3.2.4 Expected work remaining at failure point	Unlikely that sufficient funds will be available to start up by need date.
	3.2.5 Worst plausible case work remaining at failure	Unlikely that sufficient funds will 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 will 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 lifecycle costs)		
Total	(unescalated)	$22,100M

B.1.2 Alternative FBSR 1A, Fluidized Bed Steam Reforming On site 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 LDR organics destroyed Residual toxicity of secondary wastes – Hg on GAC No ammonia in final waste form Iodine & Tc partition predominantly to primary waste
	1.1.2 Mobility of primary and secondary wastes to a groundwater source	Low mobility of Tc and metals in granular product Iodine performance in final waste form is unknown
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste is intermediate (~1.2x, incl. ~10% coal) No secondary liquid
1.2 Long-term risks upon successful completion	1.2.1 Confidence in estimated residual toxicity	Destruction of all organics in DMR and/or TO Mercury – high confidence of partitioning to GAC Moderate-high confidence in I partitioning to primary wastes High confidence Tc & 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 I-129 or Tc-99 because of low rate of water available for transport to the groundwater from disposed primary waste in IDF. High confidence in nitrate/nitrite and ammonia destruction. Leaching of all COCs is mitigated by minimal transport of rainfall thru vadose zone, minimizing mobilization of contaminants to the groundwater.
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in total volume of primary and secondary waste form
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 future leaks. Consumption of entire budget will 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	Multiple hazards; 34 high-consequence worker hazards 1 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
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 1E6 gallons waste treated)

Alternative FBSR 1A		
	2.3.3 Transfer/process tank (onsite) spills	Low onsite transportation spills
	2.3.4 Offsite transportation spills	Low offsite 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 Kgal fuel, 984 MT coal, 19 GWh, 416 deliveries per 1E6 gallons 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 HLW campaign because of slow/late start-up of FBSR
	2.4.4 Risk of additional delay	High risk of additional delay due to technical issues
3 Likelihood of successful mission completion (including affordability and robustness to technical 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/wasteform Low expected release of rads – 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 will likely exceed the annual spending constraints.
	3.2.2 Projected peak spending	Peak funding needs will likely greatly exceed the annual spending constraints.
	3.2.3 Schedule flexibility	Moderate schedule flexibility
	3.2.4 Expected work remaining at failure point	Unlikely that sufficient funds will be available to start up by need date
	3.2.5 Worst plausible case work remaining at failure	Unlikely that sufficient funds will 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 lifecycle costs)		
Total	(unescalated)	$8,530 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 offsite disposal) Treatment 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	Offsite 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 large (1.8x) 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	Moderate uncertainty in removal of all organics by evaporation/oxidation High confidence in no change to toxicity of nitrate/nitrite and RCRA metals High confidence ammonia will 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 Tc, non-pertechnetate, or iodine COCs in secondary waste treatable in ETF High confidence offsite 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 (1.8x) and secondary liquid (~0.4x) 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 can 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
2.2 Risks to Humans (other than tank degradation)	2.2.1 Effort required to ensure worker safety	Low risk of contamination: no volatile rads, low maintenance Low risk of chemical exposure: low maintenance requirements Minimal hazardous chemicals, 0 high hazard consequences for workers; 12 medium consequence worker hazards (no SDU-related hazard for this alternative)

Alternative Grout 4B		
	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 (~0.4x), no new ETF needed Minimal solid, moderate liquid secondary waste streams generated
	2.3.2 Atmospheric discharges	Negligible atmospheric discharges of rads or COPCs
	2.3.3 Transfer/process tank (onsite) spills	Moderate onsite and moderate offsite transportation spill risk
	2.3.4 Offsite transportation spills	Moderate onsite and moderate offsite transportation spill risk
	2.3.5 Secondary waste streams generated	Minimal secondary wastes generated
	2.3.6 Greenhouse gas emissions	~30 Kgal fuel oil for evaporator boiler, 2.5 GWh electricity, 209 deliveries per 1E6 gallons treated
2.4 Duration	2.4.1 Duration to hot startup	Expect ~5 years (incl. construct 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 6)
3 Likelihood of successful mission completion (including affordability and robustness to technical risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Medium likelihood that LDR organic removal 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 Demonstrated effectiveness with Hanford waste and offsite 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 Vitrification
	3.1.4 Ability to incorporate future advances	Readily incorporate future advances
3.2 Likelihood & consequences of failing to complete due to resource constraints	3.2.1 Annual average spending	Funding needs will likely be well beneath the annual spending constraints. Likely that sufficient funds will be available to start up by need date
	3.2.2 Projected peak spending	Peak funding needs will likely be well beneath the annual spending constraints.
	3.2.3 Schedule flexibility	Flexible process (simple shut down, common construction methods) Unknown if vendor needs to or could expand capacity
	3.2.4 Expected work remaining at failure point	Likely that sufficient funds will be available to start up by need date

Alternative Grout 4B		
	3.2.5 Worst plausible case work remaining at failure	Likely that sufficient funds will 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 (only one for Class A) Alternative sources of key materials may need development in long term
4. Life Cycle Costs (discounted lifecycle costs)		
Total	(unescalated)	$6,450 – 7,950 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 for phases 1-2) Treatment 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 (offsite disposal) Offsite disposal does not have a pathway to potable water due to geology Phase 3 (onsite disposal) Low groundwater impact of rads or chemicals because of low rate of water available for transport to the groundwater through vadose zone Getter for iodine (or vault) expected to enable meeting concentration limits beyond compliance period Reduced inventory remaining onsite
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste is large (1.8x) 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	Moderate uncertainty in removal of all organics by evaporation/oxidation High confidence in no change to toxicity of nitrate/nitrite and RCRA metals High confidence ammonia will 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 COCs in secondary waste treatable in ETF Phases 1-2 No impact of inventory and behavior of Tc, non-pertechnetate, or iodine High confidence offsite disposal does not have a pathway to potable water due to geology Phase 3 High confidence in low groundwater impact of rads or chemicals because of low rate of water available for transport to the groundwater through vadose zone Moderate confidence in iodine getter performance beyond compliance period

Alternative Grout 6		
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in predicted total of primary (1.8x) and secondary liquid (~0.4x) 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 can 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 rads, low maintenance Low risk of chemical exposure: low maintenance requirements Minimal hazardous chemicals, 0 high hazard consequences for workers; 12 medium consequence worker hazards (no SDU-related hazard assumed for this alternative)
	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 (~0.4x), no new ETF needed Minimal solid, moderate liquid secondary waste streams generated
	2.3.2 Atmospheric discharges	Negligible atmospheric discharges of rads or COPCs
	2.3.3 Transfer/process tank (onsite) spills	Moderate onsite and moderate offsite transportation spill risk
	2.3.4 Offsite transportation spills	Moderate onsite and moderate offsite transportation spill risk
	2.3.5 Secondary waste streams generated	Minimal secondary wastes generated
	2.3.6 Greenhouse gas emissions	~30 Kgal fuel oil for evaporator boiler, 2.5 GWh electricity, 209 deliveries per 1E6 gallons treated
2.4 Duration	2.4.1 Duration to hot startup	Expect ~5 years to start up (incl. construct 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
3 Likelihood of successful mission completion (including affordability and robustness to technical risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Medium likelihood that LDR organic removal 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 for Phase 1 with Hanford waste and offsite disposal in Test Bed Initiative

Alternative Grout 6		
	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 Vitrification
	3.1.4 Ability to incorporate future advances	Readily incorporate future advances
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 constraints. Likely that sufficient funds will be available to start up by need date
	3.2.2 Projected peak spending	Peak funding needs will likely be within the annual spending constraints.
	3.2.3 Schedule flexibility	Flexible process (simple shut down, common construction methods) Unknown if vendor needs to or could expand capacity
	3.2.4 Expected work remaining at failure point	Likely that sufficient funds will be available to start up by need date
	3.2.5 Worst plausible case work remaining at failure	Likely that sufficient funds will 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 (only one for Class A) for Phases 1-2 Alternative sources of key materials may need development in long term
4. Life Cycle Costs (discounted lifecycle costs)		
Total	(unescalated)	$5,770 – 6,330 M

Appendix C. Selection Criteria Assessments for Four Key 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 KEY 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 will be fully evaluated in the Report. 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 ETF and end up grouted for disposal in IDF.

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

1.1.1.3. LDR organics – Low Residual toxicity. Most organics are destroyed by the vitrification and secondary offgas process. Some organics are generated by incomplete combustion of sugar, captured in the 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, 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 which will be partitioned to the LERF-ETF facility 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 in IDF with unknown long-term behavior.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas / carbon footprint differences across alternatives; non-discriminatory [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
[MOEs: estimated peak groundwater concentration at IDF PA compliance point over ~1K years (to DOE O 435.1; IDF PA compliance period); identify peak to 10K years to address longer-term groundwater protection (post-compliance period)] – estimated peak groundwater concentration at IDF PA compliance point over ~1K years (to DOE O 435.1; IDF PA compliance period); identify peak to 10K years to address longer-term groundwater protection (post-compliance period).

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 macro-encapsulated 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 in IDF (without getters) but improvements to primary waste form could be applied to secondary wastes.

1.1.2.1.2. Technetium (Non-TcO_4 will be evaluated below in 1.2.2.2) – Most (~99%) 99Tc assumed to be retained in the primary waste form - and 2017 IDF predicted ILAW glass contribution to be 10 × lower than compliance limit. A small fraction will be captured on the HEPA filters which are crushed and macro-encapsulated in grout. Leach rates from the spent HEPAs is evaluated in the current PA but predicted quantities of Tc on HEPAs are assumed to be extremely low but do not accurately account for system full performance.

1.1.2.1.3. ^{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 in IDF. Low inventory of ^{79}Se (114 Ci see Section E.3) leads to no risk to drinking water.

1.1.2.1.4. Cs & Sr [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 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 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 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 Hg in primary vs. secondary waste form] Hg will not be retained in glass and will end up in a grouted waste form for all options. For Vit, the Hg 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 Cr in waste form] Cr will be captured in the primary waste form and leach rate dependent on the dissolution rate of the glass. Like Tc, a small fraction could be partitioned to the spent HEPA filters that are macro-encapsulated in grout and disposed in IDF.

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 Cr.

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 at SALDS. (Note: Flush volumes not included in water effluent totals) [Reference: RPP-RPT-63328]

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.
[MOEs: 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 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 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 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 by low rate of water to transport.

1.2.2.2. Technetium (including non-pertechnetates) – Moderate confidence overall. High confidence that partitioning of Tc 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 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 Tc will be reduced and insoluble Tc. High confidence in initial immobility of reduced Tc. The reduced, insoluble Tc 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. Tc is a key constituent of interest in the IDF PA. Tc 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 Tc, and as such the secondary waste grout Tc inventory could impact groundwater compliance limit.

1.2.2.3. Selenium-79 – High confidence in minimal risk. Limited to no data to date on the partitioning in WTP, and mobility within grout waste forms. ^{79}Se is a RCRA metal (as Se) 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 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 2017 IDF PA from secondary wastes.

[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.

[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.

1.2.2.5. 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 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 by low amount of water infiltration.

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

1.2.2.6.1. Mercury low confidence in overall fate; Hg 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 Hg 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 offgas system and some to LERF/ETF; Hg 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.

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 – low TOE would lead to higher secondary waste volume per liter of feed, which would lead to larger amounts disposed 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 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 Section 1.3.3 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 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 only an 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 SLAW 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, off-gas, 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 (Bubblers, melters, HEPAs, GAC, etc.) 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 (contamination risk due to high vapor conc 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 as well as generation of toxic offgas, increasing the risk for worker exposure. In addition, the buildup of species (e.g., Hg) 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 (Bubblers, melters, HEPAs, GAC, etc.) 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 (reference: 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 evolutions required for the vitrification process increase the exposure of hands-on workers to industrial, hazards. 38 high hazards conditions were noted by WRPS for vitrification of LAW (due to large number of maintenance activities).

2.2.2. Transportation risks – [MOEs: 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 and it is expected that all waste is disposed 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 facility 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 waste water will be sent to SALDS for each gallon of SLAW feed. (tritium is all released to the environment (SALDS) immediately)

2.3.2. Atmospheric discharges – [MOE: fraction of radionuclides and CoCs converted to vapor in offgas system] Expect 34 MT NH_3 and 4 MT "other" per 1E6 gallons feed; 0.006 mrem ^{14}C discharge (reference: RPP-RPT-63328); potential for ^{129}I.

2.3.3. Transfer/process tank (onsite) spills – [Unplanned discharges MOE: no risk of onsite spills to high risk for onsite spills (spill within facility not considered a spill for this category)] (low – only risk is transfers to LERF or 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 onsite spills during treatment compared to other options. (but all transfer lines have secondary containment)

2.3.4. Offsite transportation spills – [MOE: no risk of offsite spills to high risk for offsite spills] Low risk. No shipments of liquid and no offsite immobilized waste. Offsite transportation risks include delivery of chemicals which includes liquids such as sodium hydroxide and anhydrous ammonia, diesel fuel, and other industrial chemicals and Glass Forming chemicals/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 leading to the requirement for additional treatment capacity at the LERF-ETF facility. In addition, the short operating life of components of the vitrification process (melters, bubblers, etc.) as well as the large number of consumables (HEPAs, GAC media, etc.) lead to large volumes of solid secondary waste. The waste streams will likely contain significant portions of the ^{129}I, all the Hg, and some of each of the other CoC in the waste feed. Spent melters are placed in containers and disposed in IDF. Melters have an estimated operational lifetime of five years.

2.3.6. Greenhouse gas emissions (see 2.1.2 above) – At a minimum, treatment of 1,000,000 gallons of waste consumes 3,000,000 gallons of diesel fuel, 74 GWh of electricity, and requires approximately 800 deliveries of fuel oil, glass formers, and other process chemicals (Ref: RPP-RPT-63328).

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 SLAW vitrification facility is expected to be at least twice as large as the WTP-LAW 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 facility. In a flat-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 cost section).

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 (six months) to support HLW processing. However, startup of similar facilities indicate that is more probable that a SLAW facility would require 3 years to ramp up to full operations.

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 SLAW starts later. Additional delay to SLAW 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. See overall assumption section to capture end dates, durations, and relationships between facilities.

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 SLAW melter design and operation, along with lessons learned from DWPF and WV melters and pilot testing at CUA. 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 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 SLAW and HLW processing duration.

3. Likelihood of successful mission completion
(including affordability and robustness to technical 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 solution is cost/schedule prohibitive.

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 utilize the same flowsheet and approach as the existing WTP-LAW 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 to be 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 (Hg has been absent from testing but not believed to cause dramatic impact; pilot scale system could have differences). Consequence: Frequent shut down and component replacement. (mitigated by operation of WTP LAW that will help guide MOC for SLAW.)

3.1.1.1.2. Fire in offgas system – Low risk of failure to complete, but there is potential for fire in carbon bed; SLAW could have different offgas components (organics, NO_x) (Hg has been absent from testing but not believed to be impactful; pilot scale system could have differences). Monitoring of gasses and temperature in GAC mitigates risk. Consequence: Extended duration shut down; system redesign/rebuild. Extended delays. (mitigated by operation of WTP LAW that will help guide process for SLAW.)

3.1.1.1.3. Release of radioactive material (e.g., ^{129}I, ^{3}H) or Hg 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 it 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 WTP LAW that will help guide design and operations for SLAW.)

3.1.1.1.4. Ability to control WESP as it ages – Very low risk potential to make collection of Tc ineffective; Risk is unexpected partitioning of species under melter and offgas system operating conditions (pilot scale system could have differences). Consequence: extended duration shutdown, system redesign/rebuild. Delays. (mitigated by operation of WTP LAW that will help guide design and operations for SLAW; ability to wash Tc from HEPAs or dispose 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 SLAW waste 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 as well as 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. It should be noted 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 turn-around 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 the SLAW are sized using a different basis than the current WTP-LAW facility. (very high interconnectedness) Consequence: Challenging to run system, delayed processing, additional costs, missed milestones. (mitigated by LAW 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 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 as well as 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 as well as 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.)

- Modelling needed to control process – Very high complexity. The vitrification process is driven by compositional requirements to produce a durable glass that is flowable, free of crystals and secondary phases, and with the conductivity needed for proper joule heating. The glass composition models predict the glass viscosity, liquidus temperature, PCT and VCT response, solubility of key components (S, Cr, etc.), and electrical conductivity. The model is also used to predict glass composition for reporting purposes. Uncertainty in sample analysis accuracy. 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, 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.

- Durability
  - PCT and VHT responses are modeled with no feedback mechanism in place during processing if the models are wrong. It will not be known that the glass did not meet durability limits unless future testing indicated 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 utilizes a simple model for single pass glass retention for each species in the feed to determine 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 SLAW vitrification facility could use commercially available equipment (e.g., exhaust fans, mixers, pumps), most components are similar/of a type systems modified for the SLAW facility and some systems are complete bespoke (melters, film coolers, etc.) Consequence: need to redesign/rebuild, causing mission delays. (mitigation is to get business to make replacement; build in onsite shop; purchase extras)

3.1.1.2.4. Overall flowsheet integration complexity

The flowsheet for a vitrification facility for SLAW is extremely complex. The recycle of offgas condensate to the front end creates variability in the feed, a large number of glass forming chemicals 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 is composed 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 ~six months, requiring frequent maintenance on the melters to be balanced with the operating schedule. Operating experience from WTP-LAW will help with the SLAW 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 as well as 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 supernate 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 will help with the SLAW 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 utilize the same flowsheet and approach as the existing WTP-LAW 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 DFLAW feed should reduce uncertainty in the partitioning of these species while the SLAW 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 SLAW 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 SLAW 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 incorporate 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 constrained annual SLAW budget]

The funding needs for a SLAW vitrification facility will likely exceed the annual spending constraints for a SLAW facility ($450M/yr).

3.2.2. Projected peak spending [MOE: Projected peak spending level (SLAW only) against constrained annual SLAW budget]
The peak funding needs for a SLAW vitrification facility will likely greatly exceed the annual spending constraints for a SLAW 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 SLAW 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 $ shortfall/timing; describe when it fails; MOE is consequence only)

A SLAW 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 SLAW 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 $ shortfall/timing; describe when it fails; MOE is consequence only)

Construction of the facility does not complete and never starts up. Start of SLAW mission is delayed. Worst case is to commit to vitrification option and then funding is not allocated. Consequence: delay of initiation of SLAW 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., Offsite vendor; special ingredient; sole source provider…)
The refractory used for the melters and other components have a single US 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 lab may not be able to handle the sample load from SLAW 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 SLAW 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 lifecycle costs)
Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (all costs are unescalated)

Total: $22,100 M

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

$7,500 M (includes $800 M commissioning costs)

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

$605 M R&D

4.2. *Operations costs*

$14,000 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. <u>Long-term effectiveness</u>
<u>(environmental and safety risk after disposal)</u>

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 will be fully evaluated in the Report. 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 FBSR and in the off-gas system, are essentially nondetectable in the primary waste form, but the off-gas still contains some NO_x gas species. Nitrates were destroyed to detection limit levels (0.002 wt%) in the mineralized product, and overall offgas NOx destruction was measured at between 91-94%, exceeding the goal for the Hanford LAW and WTP secondary waste simulants tests. (THOR Treatment Technologies, "Report for Treating Hanford LAW and WTP SW Simulants: Pilot Plant Mineralizing Flowsheet," Project number 29387, Document number RT-21-002, Revision 1, April 2009). 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 Hg. All Hg is presumed to evolve to the off-gas. All primary offgas components will have mercury contamination and secondary offgas components will have Hg contamination up to the GAC. Hg captured on the sulfur-impregnated GAC will 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 does not introduce ammonia into the system. Ammonia and related compounds are likely produced in the 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 across alternatives; non-discriminatory [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

MOEs: estimated peak groundwater concentration at IDF PA compliance point over ~1K years (to DOE O 435.1; IDF PA compliance period); identify peak to 10K years to address longer-term groundwater protection (post-compliance period)] – Selected findings from the ASTM 1285 short-term and long-term durability testing, SPFT testing, and PUF testing of the FBSR granular waste form produced from bench-scale, pilot-scale and engineering scale testing indicate that (1) ASTM C1285 (Product Consistency Test) releases are below 2 g/m^2 (target) which means short term, static release is comparable to a borosilicate glass[1], (2) Single Pass Flow-Through test data for Si from the 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) Pressure Unsaturated Flow-through test data indicates that Rhenium release (analogue for Tc) from the multiphase FBSR NAS granular product is an order of magnitude lower than ^{99}Tc release from LAW glass (LAW AN102) (SRNL-STI-2011-00387, Rev. 0; SRNL-RP-2018-00687, Rev. 0).

1.1.2.1.1. Iodine – Iodine is expected to partition predominately to the granular product. Release rates for iodine are below the 2 g/m^2 target (ASTM C1285 (Product Consistency Test)) for the FBSR granular product and the monoliths (SRNL-STI-2011-00387, Rev. 0). However, PCT is not indicative of long-term IDF performance, no comparative performance assessment exists for FBSR. Some iodine may be sorbed onto the GAC, quantity is uncertain. Iodine mobility to ground water is likely limited during the first 1000 years.

1.1.2.1.2. Technetium (Non-TcO_4 will be evaluated below in 1.2.2.2) Tc mobility to ground water is limited during the first 1000 years due to facility performance – Most (~99%) ^{99}Tc will be retained in the primary waste form which exhibits very low leach rates (SRNL-STI-2011-00387, Rev. 0)[2]. The release rates will likely be comparative to ILAW glass, but dependent on partitioning. A small fraction will be captured on the HEPA filters which are crushed and macro-encapsulated in grout. Leach rates from the spent HEPAs is evaluated in the current PA, but the inventory to be disposed is TBD. Expect about same amount on HEPA filters as in Vitrification. Better single pass retention of Tc in primary waste form vs. vitrification, leading to less Tc in offgas/HEPA.

[1] Accounting for the surface roughness of the mineral granules demonstrates that the FBSR product leach rate is two orders of magnitude lower than the 2 g/m^2 target and, when the surface roughness of the mineral granules is ignored compared to glass, that the FBSR product has an equivalent leach rate to vitreous waste forms (SRNL-STI-2011-00387, Rev. 0).

[2] XAS data on Tc indicates that the +7 oxidation state in the sodalite cage is between 65-79% in the 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 Tc is insoluble in the sodalite cage, while the +4 fraction of the Tc is insoluble in the oxide and/or sulfide form (SRNL-STI-2011-00387, Rev. 0).

1.1.2.1.3. ^{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 in IDF. Expect about same amount on HEPA filters as in Vitrification. Minimal impact due to limited quantity; 114 Ci total in tank farm (per RPP-ENV-58562, R3 - see 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
[Cs and Sr 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 ~1K years (to DOE O 435.1; IDF PA compliance period); identify peak to 10K 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. 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 (SRNL-STI-2011-00387, Rev. 0)[3]. Only failures in TCLP to date were for elements intentionally spiked above realistic limits.

1.1.2.4.1. Mercury [MOE is retention of Hg in primary vs. secondary waste form] – Hg 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 Cr in waste form] – Cr will be captured in the primary waste form with very low leach rates. Like Tc, a small fraction could be partitioned to the spent HEPA filters that are macro-encapsulated in grout and disposed in IDF. Expect geopolymer waste form to 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.

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[3] TCLP analyses for most of the RCRA metals were well below corresponding Universal Treatment Standards (UTS) (40 CFR 268.48 | Non-wastewater) (SRNL-STI-2011-00387, Rev. 0). However, some TCLP analyses for Sb, Cd, and Cr exceeded UTS limits depending on the laboratory performing the analyses. After additional evaluation, only the Cr analyses for the simulant exceeded the UTS; however, the granular product made using radioactive waste passed TCLP for all RCRA metals including chromium. It has been suggested that the iron oxide catalyst, added to enhance denitration, could be used as a co-reactant to sequester Cr as $FeCr_2O_4$ (SRNL-STI-2011-00387, Rev. 0).

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, HEPAs, 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*).

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.
[MOEs: 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 (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 CRR, 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 Hg to sorb onto GAC based on pilot scale testing but Hg 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. Single pass capture is high and minimal amounts in secondary waste form (GAC). Low leachability in waste form.[4]

1.2.2.2. Technetium (including non-pertechnetates) – High confidence that nearly all Tc is captured in primary waste form; remainder (minimal) is captured in HEPA filters.

[4] Release rates for iodine are expected to be below the 2 g/m^2 target (ASTM C1285 [Product Consistency Test]) for the FBSR granular product and the monoliths (SRNL-STI-2011-00387, Rev. 0).

Non-pertechnetate would be expected to decompose in DMR and behave similar to pertechnetate from waste.

1.2.2.3. Selenium-79 – Medium confidence that selenium will behave similarly to sulfur and be incorporated into primary waste form with low leach rates. Chemistry is expected to mimic sulfur, but untested for FBSR. High confidence in small inventory, 144 Ci total (per RPP-ENV-58562, R3).

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) waste form.

1.2.2.6. RCRA metals – High confidence that RCRA metals (except Hg) will be effectively immobilized in primary waste form with low leach rates. Hg 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 granular primary waste form initially, but no long-term testing on oxidation.

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.

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 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 only an 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 SLAW 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 the 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 SLAW feed itself, the process feed streams include liquid nitrogen and oxygen, alumina, clay powder, coal, fuel oil, activated carbon, sodium hydroxide, and sodium silicate solution. The process also produces gases (such as 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 space, and 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, alumina, activated carbon) 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 – [MOEs: 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 it is expected that all waste is disposed in the IDF leading to low transportation risk. Granular waste volume is ~1x the liquid waste volume.

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. For the geopolymer monolith primary waste form option, water is added which 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 not expected to be discriminator. Oxidation of organic CoCs, Hg capture, ^{129}I and ^{99}Tc and ^{14}C capture, destruction of nitrates and NO_x, gas scrubbing, and filtration for both vit and FBSR are expected to achieve regulatorily compliant results for air emissions.

2.3.3. Transfer/process tank (onsite) spills [Unplanned discharges MOE: no risk of onsite spills to high risk for onsite spills (spill within facility not considered a spill for this category)] – Minimal risk of onsite spills (all transfer lines have secondary containment). No liquids are discharged from facility.

2.3.4. Offsite transportation spills [MOE: no risk of offsite spills to high risk for offsite spills] – No shipments of liquid and no offsite immobilized waste in the case of disposal at IDF. Offsite transportation risks include delivery of chemicals which includes 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 comparable to vitrification)

2.3.6. Greenhouse gas emissions (see 2.1.2 above) – At a minimum, treatment of 1,000,000 gallons of waste consumes 984 MT of coal, 200,000 gallons fuel or natural gas, 19 GWh of electricity, and requires nearly 416 deliveries of clay, coal, and process chemicals (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 about nine years (up to now) to start radioactive feed after initial plant startup, that was mainly due to several issues identified during IWTU plant startup that were neither identified nor resolved during pre-construction 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 SLAW 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 SLAW, 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 SLAW processing starts later. Additional delay to SLAW startup extends 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. Visit overall assumption set to capture end dates, durations, and relationships between facilities.

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 similar waste to produce the mineralized waste form in an integrated system. Feed system and offgas system are complex. Limited knowledge of waste form 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 affordability and robustness to technical 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: 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 FBSR alternative will utilize a similar feed flowsheet and approach as the existing WTP-LAW facility. Portions of the process have been extensively tested using pilot scale systems, but for other applications and waste streams. Uncertainty remains in the partitioning of selected species, but 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. Failure 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, TN has operated since the 1990s, using similar mineralizing product chemistry. However, corrosion of process gas filters has been a cause of delay for the IWTU. This issue has been addressed with more pilot/demonstration testing and new filters have been installed in IWTU, and are now undergoing additional testing. Other potential corrosion issues include potential corrosion of off-gas 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: Frequent shut down and component replacement, delaying the mission completion and high costs. (mitigated by operation of IWTU and pilot testing that will help guide MOC; moderately easy to shut down and restart) (note: idling is not practical for more than a few days.)

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. SLAW is expected to contain organics and nitrates, which if not efficiently destroyed in the DMR and CRR, could encourage oxidation of GAC particles and even fire in the carbon bed. GAC is downstream of oxidizer, 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 shut down, 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., Hg, NO_x) (above permit) to atmosphere. (Tc/I radionuclides are not vaporized as much as with vit) Risk is unexpected partitioning of species under DMR/PGF and offgas system processing due to operating conditions, or failure of off-gas 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 off-gas system components (such as 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 I partitioning. Low uncertainty. Liquid waste variability and rapid reactions could impact consistent sequestration of the iodine. Consequence: excess partitioning to offgas system requiring mitigation. (mitigated by adding/modifying a 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 is based on the crystalline form of the product and ability to consistently incorporate CoCs in the cage and the reducing chemistry for Tc (SRNL-STI-2011-00387, Rev. 0). Only limited work has been done on variability and consistency of the granular waste form produced from treating the high salt solution in an FBSR and testing of radionuclide and metal retention, but presumably would be worked prior to construction and start up. Consequence: high consequences that waste form leaches radionuclides or metals and cannot be disposed without additional processing. (Mitigation method for off-spec material could include placing the product in a High Integrity Container, or offsite 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 SLAW waste 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 as well as worker protections to prevent exposure. The process contains many items that require routine hands-on maintenance or replacement. The large and extensive treatment system represents an interdependent and complex system. Offgas system is similar to IWTU (without scrubber) and variations have been tested extensively in previous pilot scale test rigs. 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)[5]

- 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
- Offgas
  - 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. Process variability vs. clay/alumina composition and operating conditions is not tested for all waste compositions to consistently achieve the right crystalline structure. Consequence: potential low throughput; poor product quality
- Modelling needed to control process – Very high complexity. The FBSR process is driven by compositional requirements to produce a durable waste form that is flowable, free of secondary phases, and of a reliably durable form. There are no composition models at this time to predict the parameters of importance to the waste form. Reactions in the DMR gas phase occur within seconds, requiring a constantly vigilant control system. Consequence: see items below. A composition and control model could be developed as technology is matured; Expect FBSR is moderately robust toward composition and operation with few parameters needed. Testing assumed during development would be used to develop models/control process.
  - Failure modes for improper operation

[5] Very low or low complexity/consequences unless specified otherwise

- Improper mineralized product production
  - Producing wrong mineral product or an amorphous product due to inability to control additives and process conditions would impact leachability 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 (Na, Cr, halides, radionuclides, etc.) can lead to variations in the primary waste form chemistry and mineralogy which may impact the 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.
- Failure to control key temperatures in the DMR, PGF, TO, and off-gas system
  - Temperatures too low could cause off-spec 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 SLAW FBSR facility would be first-of-a-kind, but some components are used in related or other systems in use. 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 a FBSR facility for SLAW is more complex than for a grouting facility and similarly complex 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 off-gas system includes high and low-temperature (HEPA) filtration, thermal oxidation, GAC bed Hg absorption, wet scrubbing, and off-gas cooling and reheating. The recycle of spent scrubber solution to the feed system can add some variability to the waste feed composition which must be accounted for in the feed analyses and clay additive determinations.

Operating experience from WTP-LAW 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, Process Gas Filter, Product Handling System, off-gas 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 as well as process chemicals such as clay, coal, alumina, thermal oxidizer 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, thermal oxidizer fuel, and geopolymer additives. The infrastructure for the clay, thermal oxidizer fuel, and geopolymer additives is similar to relevant infrastructure in other industries. Cross-site supernate 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 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 SLAW 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 utilize 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 SLAW 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 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, Process Gas Filter, 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 High Integrity Containers, 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 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." [Reference: NRC 2011, "Wasteforms Technology and Performance, Final Report," National Research Council of the National Academies, Committee on Wasteforms Technology and Performance, National Academies Press, Washington, DC.]. Non-pertechnetate is not an issue for the FBSR process since any non-pertechnetate will 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 incorporate 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 materials – water, steam, clay, coal, alumina, thermal oxidizer 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 constrained annual SLAW budget]

The funding needs for a SLAW FBSR facility will likely exceed the annual spending constraints for a SLAW facility ($450M/yr).

3.2.2. Projected peak spending [MOE: Projected peak spending level (SLAW only) against constrained annual SLAW budget]

The peak funding needs for a SLAW FBSR facility will likely greatly exceed the annual spending constraints for a SLAW 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 has 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. A controlled cold shut down requires ~1-2 days for shutdown, and 1-2 weeks for restart. Using two FBSRs, 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 $ 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 SLAW 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 $ shortfall/timing; describe when it fails; MOE is consequence only)

Construction of the facility starts and stops prior to start up. Start of SLAW 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 SLAW 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., Offsite 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.

4. Lifecycle Costs

(discounted lifecycle costs)
Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (all costs are unescalated)

Total: $8,530 M

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

$2,570 M (includes $330M commissioning costs)

$350 M Evaporator (includes $45M commissioning costs)

$605 M R&D

4.2. Operations costs

$5,005 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 will be fully evaluated in the Report. 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 across alternatives for long term; non-discriminatory [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

[MOEs: estimated peak groundwater concentration at IDF PA compliance point over ~1K years (to DOE O 435.1; IDF PA compliance period); identify peak to 10K 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. Offsite 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: (NP 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. Offsite 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 Tc.

1.1.2.1.3. ^{79}Se – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci see Section E.3). No impact to Hanford groundwater due to disposal of primary waste form offsite. Offsite 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
[Cs and Sr 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 ~1K years (e.g., DOE O 435.1 compliance period); identify peak to 10K years to address longer-term groundwater protection] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Offsite 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 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 onsite SLAW evaporator. Offsite 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 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 Hg in primary vs. secondary waste form] – Sequestered by sulfide reaction with BFS and low inventory. Grout waste form will be TCLP compliant (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.2. Chromium – Cr(VI) sequestered by redox w reductants in BFS and precipitation as hydroxide with alkali. Grout waste form will be TCLP compliant (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 [Reference: RPP-RPT-63426]. 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 (earthquake, catastrophic flood, volcano, etc.) are assessed as indistinguishable across all technologies and disposal locations.]
[MOEs: 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. Moderate confidence LDR organics can be removed/destroyed to beneath regulatory limits; additional evaluations, analyses, and testing planned; alternative is sending to LAW Vit

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] Bounding case of 1.8 ratio per p. A-22 from the Final EIS (DOE/EIS-0082-S2, June 2001), *Savannah River Site Salt Processing Alternatives; Aiken, South Carolina*; and Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington (TC & WM EIS) (DOE/EIS-0391) provides a value of 1.4X (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. Offsite 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. Offsite 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. Selenium-79 – No impact to Hanford groundwater. Offsite 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. Offsite 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. Offsite 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 – Depends on metal
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 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 is both a 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 SLAW 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 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 offsite prefab 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]. (1 high consequence hazard is not applicable to this alternative since there is no vault). Over 20 years of operation of Saltstone at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOEs: 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 rad liquid transports of decontaminated SLAW to offsite; rad liquid transport of evaporator condensate to ETF (assumed to be by truck); many offsite transports of solid radioactive materials (grouted waste) from vendor to offsite.

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 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 1E6 gallons SLAW. Negligible particulates from dry feed additions [per RPP-RPT-63426].

2.3.3. Transfer/process tank (onsite) spills (Unplanned discharges) [MOE: no risk of onsite spills to high risk for onsite 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 SLAW to offsite vendor and evaporator condensate to LERF/ETF. Mitigated by experience with shipment of radioactive liquids.

2.3.4. Offsite transportation spills [MOE: no risk of offsite spills to high risk for offsite spills] – Moderate risk of liquid spills during transport of liquid decontaminated SLAW to offsite 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 Kgal per 1E6 gallons waste).

2.3.6. Greenhouse gas emissions [MOE: Calculated fuel/power/deliveries] – At a minimum, treatment of 1,000,000 gallons of waste consumes ~30,000 gallons of boiler fuel oil for LDR evaporation, 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 1A alternative [RPP-RPT-63426]. There would be additional emissions from transport of the liquid to the vendor and shipping to offsite. Expect shipments of ~46,000 grouted waste form boxes to distant disposal location(s).

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[2] 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) ~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 the waste.

2.4.2. Duration to full capacity (additional years) 0 – 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. LDR removal has had only limited testing 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 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 SLAW and HLW processing.

3. Likelihood of successful mission completion
(including affordability and robustness to technical 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] – The grout alternative will utilize 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 could be removed to be below regulatory limits. 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 offsite 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 SLAW waste 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.

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

- Oxidative treatment – 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 Hg.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container box disassembly and emplacement at -offsite 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-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 offsite grouting facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernate treatment; reduces SST leakage risk; reduce cross site transfer of supernate.

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

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 Savannah River (similar process, scale, and waste operating since 1990), Idaho, 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 (glycolate destruction at SRS for DWPF effluents, etc.) 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 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 modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Unknown if vendor needs to or could expand capacity but expect that vendor could accommodate 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 constrained annual SLAW budget] – Low likelihood of failure. The funding needs for offsite immobilization will likely be beneath the annual spending constraints ($450M/yr).

3.2.2. Projected peak spending [MOE: Projected peak spending level (SLAW only)] against constrained annual SLAW budget – Low likelihood of failure. The peak funding needs for offsite immobilization will likely be beneath the annual spending constraints ($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 $ shortfall/timing; describe when it fails; MOE is consequence only)

Operation does not start or stops until funding is available. Start of SLAW mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: delay of initiation of SLAW 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] (Note: assume it fails due to resources; reason is $ shortfall/timing; describe when it fails; MOE is consequence only)
(e.g., Offsite 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 utilize 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.

Offsite 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 lifecycle costs)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. All costs are unescalated

Total: $6,450-7,950 M

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

$350 M Evaporator (includes $45M commissioning costs)

$120 M R&D

4.2. Operations costs

$5,980 – 7,480 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 will be fully evaluated in the Report. 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 – High residual toxicity. No reduction in inherent toxicity vs. feed vector; MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.

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 across alternatives for long term; non-discriminatory [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 [MOEs: estimated peak groundwater concentration at compliance point over ~1K years (e.g., DOE O 435.1; IDF PA compliance point and period); identify peak to 10K 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 1000 years. Iodine sequestered by getter leads to enhanced retention in waste form; relative to non-getter waste form. Projected ~100X below Drinking Water Standard (DWS, aka MCL) 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.

Onsite inventory from SLAW reduced by ~50% or more. Inventory remaining onsite will scale proportionally to peak dose at point of compliance. In addition, Iodine mobility to onsite ground water is limited during the first 1000 years. Offsite: No impact to Hanford groundwater due to disposal of primary waste form offsite. Offsite 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: Tc mobility to ground water is limited during the first 1000 years due to facility performance. Blast-furnace slag (BFS) sequesters Tc providing high performance for Tc; ~10X 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 Tc 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 SLAW grout and the secondary waste grout. Onsite inventory from SLAW reduced by ~50% or more. Inventory remaining onsite will scale proportionally to peak dose at point of compliance. In addition, Tc mobility to ground water is limited during the first 1000 years. (NP will be evaluated below in confidence) Offsite: No impact to Hanford groundwater due to offsite disposal. Offsite 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. ^{79}Se – Sequestered by waste form Minimal impact due to limited quantity (114 Ci see section E.3). Onsite inventory reduced by this alternative. Offsite: No impact to Hanford groundwater due to offsite disposal. Offsite 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
[Cs and Sr 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 ~1K years (to DOE O 435.1; IDF PA compliance period); identify peak to 10K years to address longer-term groundwater protection (post-compliance period)] – Onsite: Nitrate/nitrite mobility to ground water is limited during the first 1000 years. 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 (ref. PNNL-28992, Fig 4-3). Onsite inventory reduced by this alternative in roughly the same fraction as the volume disposed.

Offsite: No impact to Hanford groundwater due to offsite disposal. Offsite 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 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. Offsite 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 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. Onsite: waste form has reduced toxicity. Grout waste form will be compliant. Offsite: 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 Hg 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 be TCLP compliant (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)] – 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 Cr. To limit mobility beyond the period of compliance Cr 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 be TCLP compliant (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 Cr. Offsite: 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 [Reference: RPP-RPT-63426]. However, the reference did not include evaporation step, which would add ~0.38 gallons of liquid effluent disposed at SALDS. Onsite: total volume remaining onsite reduced by 30% or more.

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.]
[MOEs: 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. Moderate confidence LDR organics can be removed/destroyed to beneath regulatory limits; 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 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.

[1] Bounding case of 1.8 ratio per p. A-22 from the Final EIS (DOE/EIS-0082-S2, June 2001), *Savannah River Site Salt Processing Alternatives; Aiken, South Carolina*; and Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington (TC & WM EIS) (DOE/EIS-0391) provides a value of 1.4X (p. 2-28).; range is 1.4 – 1.8

^{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 SLAW iodine inventory could impact groundwater compliance limits. However, this is mitigated by the lack of driving force due to minimal flow of water in the unsaturated vadose zone, preventing it from actually contacting subsurface aquifers. Offsite: No impact to Hanford groundwater. Offsite 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 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 Tc but there is an unknown behavior of non-pertechnetate. High confidence in initial immobility of reduced Tc. The reduced, insoluble Tc 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. Tc is a key constituent of interest in the IDF PA. Tc can define waste classification and select tanks have Tc concentrations that approach the Class A limit[3]. However, this is mitigated by the lack of driving force due to minimal flow of water in the unsaturated vadose zone, preventing it from actually contacting subsurface aquifers. Offsite: No impact to Hanford groundwater. Offsite 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. Selenium-79 – 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-ENF-58562, R3). However, this is mitigated by the lack of driving force due to minimal flow of water in the unsaturated vadose zone, preventing it from actually contacting subsurface aquifers. Offsite: No impact to Hanford groundwater. Offsite 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.

1.2.2.4. Nitrates/nitrites – Onsite: 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 compliance limits using a projection of a non-optimized grout waste form disposed in IDF.

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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

As such there is uncertainty in the overall impact to GW. However, this is mitigated by the lack of driving force due to minimal flow of water in the unsaturated vadose zone, preventing it from actually contacting subsurface aquifers. Offsite: No impact to Hanford groundwater. Offsite 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 in IDF poses minimal impact. Offsite: No impact to Hanford groundwater. Offsite 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 Hg sulfide formation but low confidence in Hg 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 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 (Fe, carbonate, Ba) 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.

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 Section 1.3.3 for more detail)].

Startup in 4 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 since retrievals would be earlier than currently scheduled and would support HLW, allowing the lowest time for additional corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – depending on when it happens, loss of specific DSTs is more or less impactful. During the initial phase when liquid is shipped offsite, it is less dependent on the infrastructure items, like the cross site transfer line. But in later phases when it transitions to onsite production of grout, it is dependent on the cross site transfer line, specific feed piping, tank utilization, etc. Since this has both East and west area facilities, it 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 SLAW 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 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 Vit); construction would be 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 offsite prefab 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 vault). Over 20 years of operation of Saltstone at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOEs: 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 offsite transports of solid radioactive waste form packages to distant location(s). Practical impact will be negligible since 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 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 1E6 gallons SLAW. Negligible particulates from dry feed additions [per RPP-RPT-63426].

2.3.3. Transfer/process tank (onsite) spills – (Unplanned discharges) [MOE: no risk of onsite spills to high risk for onsite 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. Offsite transportation spills [MOE: no risk of offsite spills to is high risk for offsite spills] – Large numbers of radioactive shipments, both liquid and solids.

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 Kgal per 1E6 gallons waste).

2.3.6. Greenhouse gas emissions [MOE: Calculated fuel/power/deliveries] – At a minimum, treatment of 1,000,000 gallons of waste consumes ~30,000 gallons of boiler fuel oil for LDR evaporation, 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).

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.

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

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. LDR removal has had only limited testing but 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 SLAW and HLW processing.

3. Likelihood of successful mission completion

(including affordability and robustness to technical 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 will utilize 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 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 (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. Suitable getter (iodine and potentially Tc) not identified / long term performance inadequate – Medium likelihood and high consequence for onsite disposal of grouted waste. 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. Offsite 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 could be removed to be below regulatory limits. 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 offsite 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. 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.)] – Grouting of the SLAW waste 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

- 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 (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 Hg.
- 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 offsite grout production facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernate treatment; reduces SST leakage risk; reduce cross site transfer of supernate.

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 supernate 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: Offsite 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 off-site successfully demonstrated during Test Bed Initiative. Grout in general is demonstrated; saltstone at Savannah River (similar process, scale, and waste operating since 1990) Idaho, 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 (glycolate destruction at SRS for DWPF effluents, etc.) 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, 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.] – 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 incorporate 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.

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. Additional time to begin Phase 4 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 constrained annual SLAW budget] – The funding needs for a SLAW grout facility will likely be beneath the annual spending constraints for a SLAW facility ($450M/yr). Spending includes both East plant construction while also paying offsite vendor and transporting waste but benefit is early start.

3.2.2. Projected peak spending [MOE: Projected peak spending level (SLAW only) against constrained annual SLAW budget] – The peak funding needs for a SLAW grout facility will likely be beneath the annual spending constraints for a SLAW facility ($450M/yr). Higher costs overall but can 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 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 $ shortfall/timing; describe when it fails; MOE is consequence only)

Operations, shipping, & disposal more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Offsite disposal option allows flexibility in the event of onsite disposal issues and offsite immobilization step mitigates onsite 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 $ shortfall/timing; describe when it fails; MOE is consequence only) – Construction of the onsite facilities does not start or stops until funding is available. Worst case is to continue offsite grout. Consequence: costs of offsite disposal and grouting must continue longer than projected. 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., Offsite 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 utilize 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 pre-selected. Offsite: or if another disposal location must be identified.

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 lifecycle costs)
Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (all costs are unescalated)

Total: $5,770-6,330 M (range based on vendor grouting cost range)

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

$730 M Grout Plant (includes $80 M for commissioning costs)

$350 M Evaporator

$120 M R&D

4.2. *Operations costs*

$4,570-5,100 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.3 REFERENCES

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Appendix D. Summary of Disposal Site, Transportation, and Off-Site Disposal Considerations

D.1 INTRODUCTION

The 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.

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.
- **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.
- **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).

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). The two supplemental LAW treatment waste forms considered for off-site disposal are grout and fluidized bed steam reforming (FBSR) waste forms. The vitrified waste forms evaluated in this study would be disposed onsite in the IDF and are not discussed in this appendix. The off-site transportation programs incorporate packaging requirements, transportation routes and schedules, documentation, transportation and disposal costs, specific technical considerations, and risk evaluation.

D.2 DISPOSAL SITES

D.2.1 Integrated Disposal Facility

Located in the 200 East Area of the Hanford Site, the IDF provides a disposal facility for LLW and MLLW. 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 (Vance, 2021).

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. 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 modified RCRA Subtitle C barrier and a leak detection system to collect leachate.

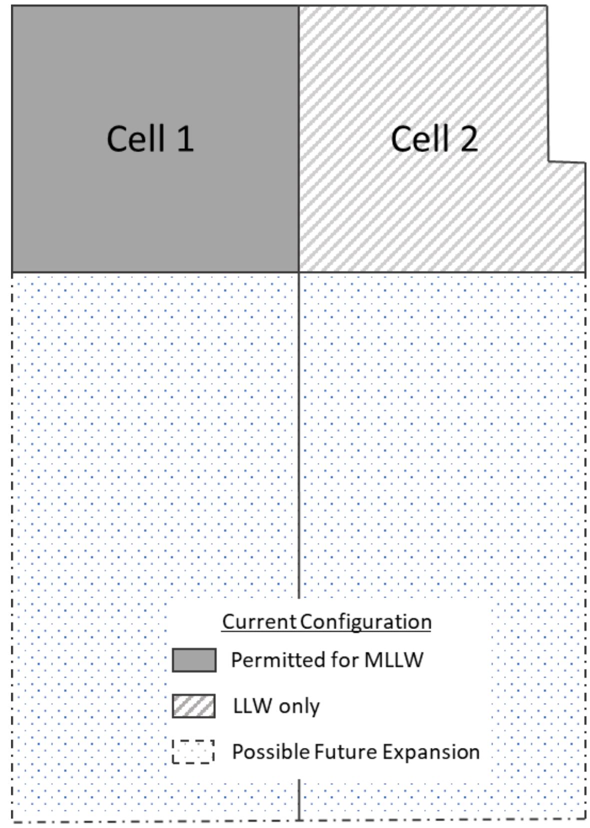

Figure D-1.Integrated Disposal Facility Configuration

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* (SRNL-RP-2018-00687).

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 10 CFR 61.55; however, as noted below, the waste acceptance criteria for the IDF contains limits for waste to be accepted.

Performance Assessment and Waste Acceptance Criteria

The IDF PA (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*) was publicly released in 2019 and contains analyses that are to be used to develop operating conditions or requirements for the disposal facility. A draft WIR (DOE-ORP-2020-01, *Draft Waste Incidental to Reprocessing Evaluation for Vitrified Low Activity Waste for Onsite Disposal at the Hanford Site*) was prepared that demonstrates that the vitrified low-activity waste from the Waste Treatment and Immobilization Plant (WTP) may be managed as LLW. As described in the draft WIR, the approach addresses the three WIR criteria: (1) removal of key radionuclides to the maximum extent technically and economically practical, (2) meets DOE M 435.1 performance objectives at 1000 years, as described in the IDF PA, and (3) a determination vitrified LAW will not exceed Class C LLW concentration limits. A final WIR Evaluation has not yet been published.

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 radioactive materials disposal license and RCRA permit (Vance, 2020). The waste acceptance criteria prohibit HLW from acceptance and disposal at IDF. Waste disposed of in IDF must meet the radiological performance objectives established in DOE M 435.1-1.

The IDF is permitted 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 must be <1% by weight volume.
- 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 O 435.1 (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 (HDWP, 2021). 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.

Waste Capacity

The IDF is currently permitted to dispose of 82,000 m^3 of MLLW (WA 7890008967) in one of the disposal cells. The permit modification request under review with Ecology would allow disposal of MLLW in both cells, with a maximum disposal capacity of approximately 505,000 m^3. Future construction could expand the disposal cells, allowing for a total maximum disposal capacity of approximately 2,260,000 m^3 (Vance, 2021).

Based on the data in Table D-1, all technologies produce waste within the disposal capacity of IDF.

Table D-1. Estimated Disposal Volumes to the Integrated Disposal Facility

	Vitrification	Grout	FBSR
WTP vitrification volume to IDF (m^3)	105,000	105,000	105,000
Waste from alternative to IDF (m^3)	83,000	380,000	255,000
Total	**188,000**	**485,000**	**360,000**

FBSR = fluidized bed steam reforming.
IDF = Integrated Disposal Facility.
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 3 mi south of the highway in Tooele County. The facility is approximately 50 mi east of Wendover, Utah, and approximately 80 mi west of Salt Lake City, Utah. The natural topography slopes slightly toward the southwest with approximately 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 1 mi^2 in size. The DOE-owned Vitro property occupies approximately 100 ac of the facility. Figure D-3 (on the next page) 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.

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.

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

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) (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 2-ft thick layer of compacted clayey native soil (Unit 4).
- **Waste**. The waste layer will not exceed a final thickness of 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 37.6 ft.
- **Radon barrier**. The top slope cover design contains an upper radon barrier consisting of 12 in. of compacted clay with a maximum hydraulic conductivity of 5×10^{-8} cm/sec and a lower radon barrier consisting of 12 in. of compacted clay with a hydraulic conductivity of 1×10^{-6} cm/sec.
- **Filter zone (lower)**. The 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 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 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 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 37.6 ft at the shoulder, for an average waste height of 18.8 ft ((0+37.6)/2).
- **Rip rap cobbles**. Approximately 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 *Utah Administrative Code* (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 61 to 90%, depending on feed vector characteristics and whether a Hanford System Plan representative feed is used or an “Early Start” feed is used.

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 (UDEQ, 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 3 million yd^3. Consequently, disposing of all Class A Hanford LAW from supplemental treatment at Clive will take from 7 to 26% 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 $pCi/m^{2\text{-}s}$, 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 3.5 ft of rock layers, 2 ft of clay, and 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 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 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)

The WCS Waste Disposal Facility 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 Off-Site 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).

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 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.

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 D-4.Clive Waste Disposal Facility

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.

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/s. 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 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 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: 6-ft and (2) rectangular: 9 ft 6-in. L × 7 ft 8-in. W × 9 ft 2-in. H (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 2 in. extra on all four sides and 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 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.

The term of the current license is through September 2024, with provision for 10-year renewals thereafter. The state of Texas takes ownership of LLWs 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.). In all grout cases, the Class B and C waste forms are produced only during the first 7 years of operations for alternatives using nominal Hanford supplemental LAW characteristics or during the first 18 years of operations (Early Start). In the FBSR case, the Class B and C waste forms are produced during the first 9 years and then periodically during the last 20 years of operations.

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.

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 (Kd) 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.

For transportation within DOE site boundaries and not in commerce, requirements are specified under DOE's directive system through DOE Orders and Manuals:

- DOE O 460.1D, *Hazardous Materials Packaging and Transportation Safety*, 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 and fluidized bed steam reforming (FBSR) 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 or FBSR LAW waste forms can be disposed of at the WCS disposal facility, in addition to all Class A waste from supplemental treatment.

D.3.2 Key Transportation Regulatory Considerations

The NRC regulates 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, *Code of Federal Regulations*, 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 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 are not anticipated to require shipping in a Type B shipping cask. Additional details on IP and Type A packages are contained in Section H.3.1 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 the various packaging types and concludes that untreated supplemental LAW liquids, treated grout waste forms, and FBSR waste forms can be transported in IPs in all off-site disposal alternatives with considerable margin. Transport of untreated supplemental LAW liquid was considered by both rail and trucks in nominal 5,000-gal containers. The regulations for determining the types of packaging also require determination of total activity of a shipment or conveyance, considering the total number of tankers in a shipment. For shipments using multiple 5,000-gal rail tank cars, shipments early in the supplemental LAW campaign may be limited. Figure D-6 depicts this. Details are provided in Section H.5 of Volume II, Appendix H.

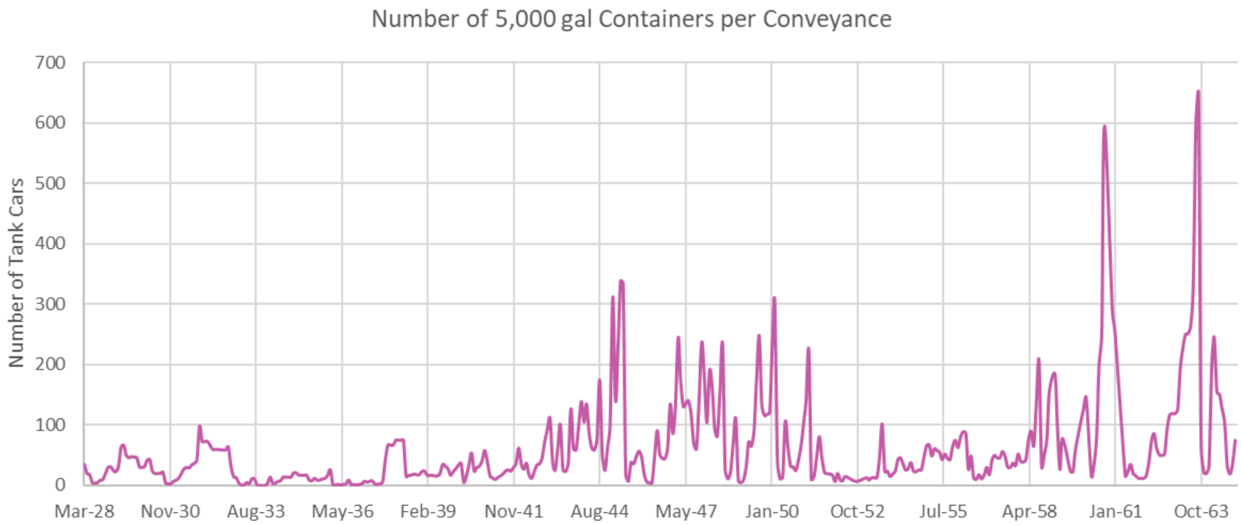

Figure D-6.Early Start Feed Vector Maximum Number of 5,000 gal Containers per Conveyance.

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 §§ 172.400 through 172.407 and §§ 172.436 through 172.441 of Subpart E
- Placarding: 49 CFR 172, Subpart F, especially §§ 172.500 through 172.519 and 172.556; and Appendices B and C
- Accident reporting: 49 CFR 171, §§ 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.

To ensure the appropriate scoping and costing, this study relies on analogue 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, would probably require preparation of an additional *National Environmental Policy Act* (NEPA) evaluation.

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 73.465(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.

The IP-2 package proposed for transporting grout and FBSR waste forms is a 8.4-m^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 or steam reformed mineral product, the IP-2 soft side containers will be managed in reusable steel overpacks (boxes). To do this, the soft-side container will be placed in the overpack, filled with grout or steam reformed mineral product, transferred to a gondola railcar, secured, and shipped for off-site disposal. The soft-side container will be removed from the steel overpack and the empty overpack will be transported back. The waste form would remain in the soft-side container and be emplaced as bulk waste if Class A or in a MCC if Class B or C (disposal at WCS only).

Two 8.4-m^3 bags will fit into one MMC. Figure D-7 shows an example of a large soft-side container that can be used to ship LSA materials. The steel overpack is not required to meet DOT packaging requirements. If grouting takes place at Perma-Fix, the overpacks will not be used.

Conceptually, the steel overpack might look like the steel boxes shown in Figure D-8, but lighter weight and with a shallower lid.

D.3.4 Transportation Campaign Schedule

It is expected that all wastes will be shipped on gondola railcars to either WCS or Energy*Solutions*. The gondola car cargo capacity is 90,910 kg (200,000 lb) per gondola railcar. The 8.4-m^3 bag with grout weighs 14,868 kg. Consequently, six bags can be transported by one gondola. The 8.4-m^3 bag with FBSR weighs 6,720 kg. Consequently, 13 bags can be transported by one gondola.

Transport of the expected grout production will require, on average, 16 gondolas per month. However, due to large variations in produced monthly volumes, transporting a monthly volume equal to 16 gondolas will require lag storage with maximum capacity of 55,903 m^3. Transporting 30 gondolas per month (which can be done with one train) will require significantly smaller lag storage capacity of 3,029 m^3. Even smaller lag storage capacity is achievable if the transportation schedule is optimized. The lag storage capacities are shown in Figure D-9. Figure D-10 shows how many transport months will be in each year when 30 gondolas per months are used. The transport would occur on average every other month.

Source: Photograph from PacTec, Inc literature.

Figure D-7.Example of Soft Side Container for Shipping Low-Specific Activity Materials

Source: Photograph from Container Technologies Industries, LLC literature.

Figure D-8.Example of a Reusable Steel Split-Cavity Overpack (actual overpack would be smaller, lighter, and with a shallower lid)

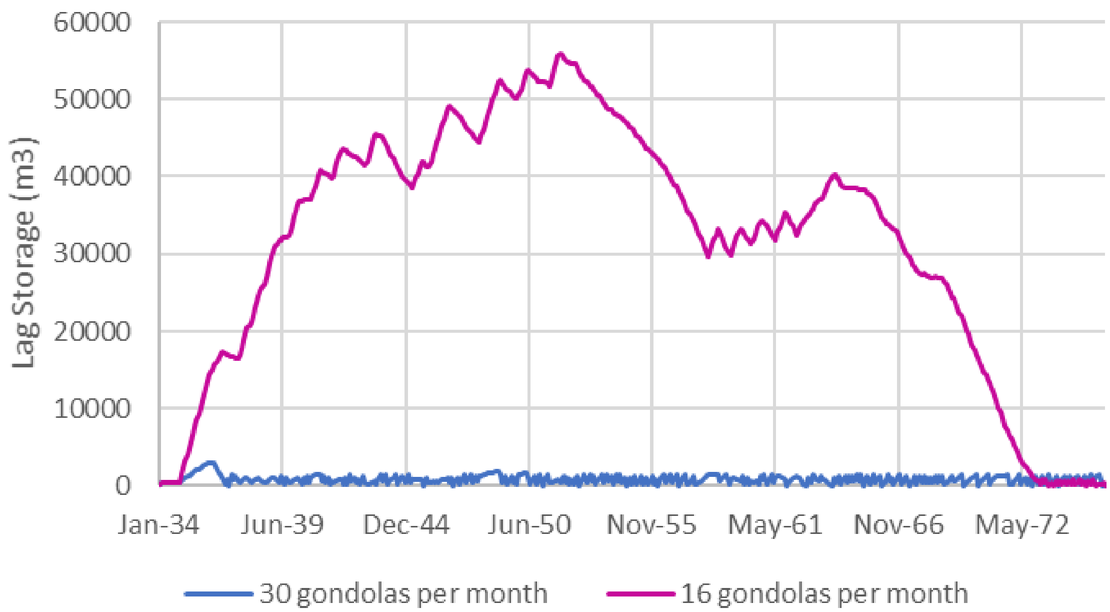

Figure D-9.Grout Lag Storage Capacity, SP9 1B Feed Vector

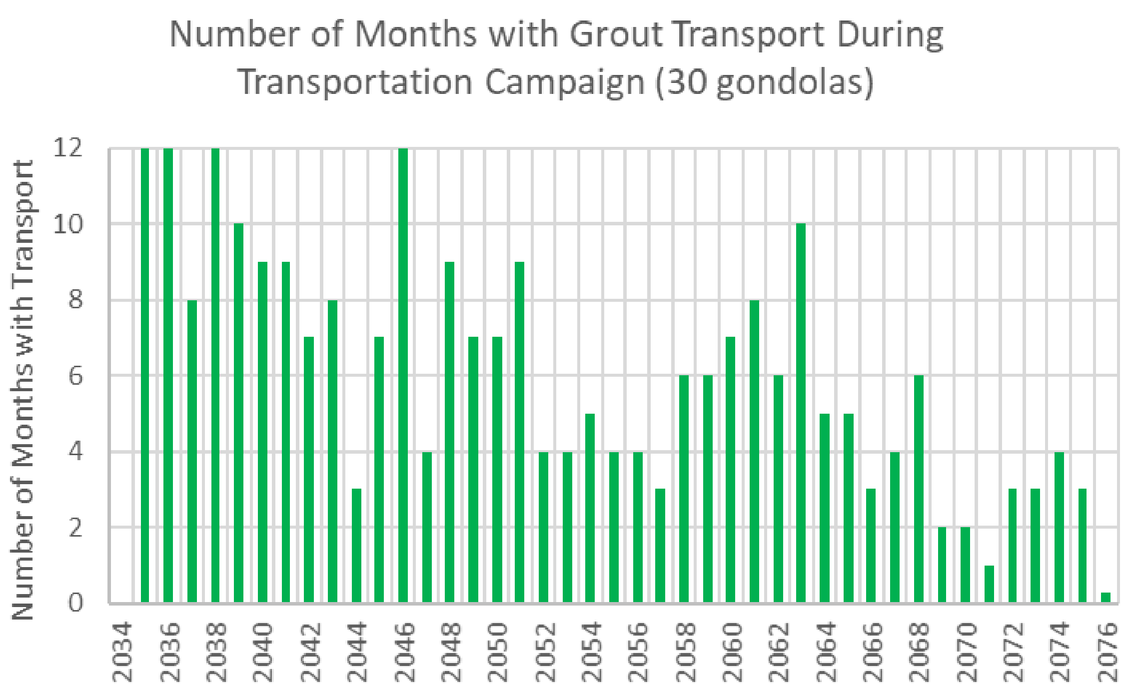

Figure D-10. Number of Months with Grout Transport, SP9 1B Feed Vector

Similar results are obtained for the FBSR waste form, with a somewhat reduced demand for the number of gondola cars shipped every other month, 10 versus 30. Higher numbers of gondola cars will be required for the Early Start variant. Details of this analysis are in section H.7.2 of Volume II, Appendix H.

D.3.5 Transportation Routes

Figure D-11 is a map of possible rail routes from Hanford/Perma Fix to WCS and Clive. The rail routes shown in Figure D-11 were generated with WebTRAGIS, the Oak Ridge National Laboratory (ORNL) 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.

Table D-2 and Table D-3 summarize the route data and Table D-4 provides a comparison of the routes.

Figure D-11. Rail Routes from Hanford (Perma-Fix) to Waste Control Specialists (Texas) and Clive (Utah)

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/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

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 grouted at Perma-Fix, 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 for shipment to WCS were used. These 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 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.

- Off-site grout generation provided by Perma-Fix is $40/gal. 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 determined to be $30/gal.

- Finally, the minimum expected cost of grout generation, based upon a contract for grouting large volumes of LAW, is $20/gal (MR-50713). 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 to Table D-7 and are plotted in Figure D-12 to Figure D-16. In addition to the total costs, the percent of the annual budget is also calculated, assuming an annual budget dedicated to the supplemental treatment of LAW is $450 million. 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 3.6 to 7.6%. 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 1.8 to 3.8%. 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.

- When the SP9 1B feed vector liquid is converted to grout at Perma-Fix, the total cost ranges from $1.95 billion to $3.5 billion and represents 11 to 19% of the annual budget of $450 million (Table D-5).
- When the Early Start feed vector liquid is converted to grout at Perma-Fix, the total cost ranges from $3.17 billion to $5.8 billion and represents 19 to 35% of the annual budget of $450 million (Table D-6).
- When Early Start feed vector liquid is converted to grout at Perma-Fix and off-site disposal continues until 2040, the total cost ranges from $1.19 billion to $2.0 billion and represents 22 to 37% of the annual budget of $450 million (Table D-7).

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, SP9 1B Feed Vector, Grouting at Perma-Fix

Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$3,503,101,228	19.0%	$2,647,431,355	14.3%	$2,098,049,546.39	11.37%
0.1	$3,488,159,634	18.9%	$2,632,489,762	14.3%	$2,083,107,952.81	11.29%
0.2	$3,473,237,041	18.8%	$2,617,567,168	14.2%	$2,068,185,359.23	11.21%
0.3	$3,458,283,447	18.7%	$2,602,613,575	14.1%	$2,053,231,765.65	11.13%
0.4	$3,443,341,854	18.7%	$2,587,671,981	14.0%	$2,038,290,172.06	11.05%
0.5	$3,428,407,260	18.6%	$2,572,737,388	13.9%	$2,023,355,578.48	10.97%
0.6	$3,413,465,666	18.5%	$2,557,795,794	13.9%	$2,008,413,984.90	10.89%
0.7	$3,398,531,073	18.4%	$2,542,861,200	13.8%	$1,993,479,391.31	10.80%
0.8	$3,383,589,479	18.3%	$2,527,919,607	13.7%	$1,978,537,797.73	10.72%
0.9	$3,368,654,886	18.3%	$2,512,985,013	13.6%	$1,963,603,204.15	10.64%
1	$3,353,713,292	18.2%	$2,498,043,420	13.5%	$1,948,661,610.56	10.56%
Max increase	4.26%		5.64%		7.12%	

Table D-6. Off-Site Grout Disposal Costs, Early Start Feed Vector, Grouting at Perma-Fix

Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$5,813,454,439	34.9%	$4,363,477,750	26.2%	$3,432,521,965.99	20.62%
0.1	$5,787,295,093	34.8%	$4,337,318,404	26.0%	$3,406,362,620.01	20.46%
0.2	$5,761,135,747	34.6%	$4,311,159,058	25.9%	$3,380,203,274.02	20.30%
0.3	$5,734,976,401	34.4%	$4,284,999,712	25.7%	$3,354,043,928.04	20.14%
0.4	$5,708,817,055	34.3%	$4,258,840,366	25.6%	$3,327,884,582.05	19.99%
0.5	$5,682,657,709	34.1%	$4,232,681,020	25.4%	$3,301,725,236.07	19.83%
0.6	$5,656,498,363	34.0%	$4,206,521,674	25.3%	$3,275,565,890.08	19.67%
0.7	$5,630,339,017	33.8%	$4,180,362,328	25.1%	$3,249,406,544.10	19.52%
0.8	$5,604,179,671	33.7%	$4,154,202,982	25.0%	$3,223,247,198.11	19.36%
0.9	$5,578,020,325	33.5%	$4,128,043,636	24.8%	$3,197,087,852.13	19.20%
1	$5,551,860,979	33.3%	$4,101,884,290	24.6%	$3,170,928,506.14	19.04%
Max Increase	4.50%		6.00%		7.62%	

Table D-7. Off-Site Grout Disposal Costs, Early Start Feed Vector, Grouting at Perma-Fix, Off-Site Disposal until 2040

Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$2,021,422,014	37.4%	$1,559,070,956	28.9%	$1,262,219,017.45	23.37%
0.1	$2,014,235,580	37.3%	$1,551,884,522	28.7%	$1,255,032,583.58	23.24%
0.2	$2,007,049,146	37.2%	$1,544,698,088	28.6%	$1,247,846,149.72	23.11%
0.3	$1,999,862,712	37.0%	$1,537,511,655	28.5%	$1,240,659,715.85	22.98%
0.4	$1,992,676,278	36.9%	$1,530,325,221	28.3%	$1,233,473,281.99	22.84%
0.5	$1,985,489,844	36.8%	$1,523,138,787	28.2%	$1,226,286,848.12	22.71%
0.6	$1,978,303,411	36.6%	$1,515,952,353	28.1%	$1,219,100,414.26	22.58%
0.7	$1,971,116,977	36.5%	$1,508,765,919	27.9%	$1,211,913,980.39	22.44%
0.8	$1,963,930,543	36.4%	$1,501,579,485	27.8%	$1,204,727,546.53	22.31%
0.9	$1,956,744,109	36.2%	$1,494,393,051	27.7%	$1,197,541,112.66	22.18%
1	$1,949,557,675	36.1%	$1,487,206,617	27.5%	$1,190,354,678.80	22.04%
Max increase	3.56%		4.61%		5.69%	

Figure D-12 through Figure D-17 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.

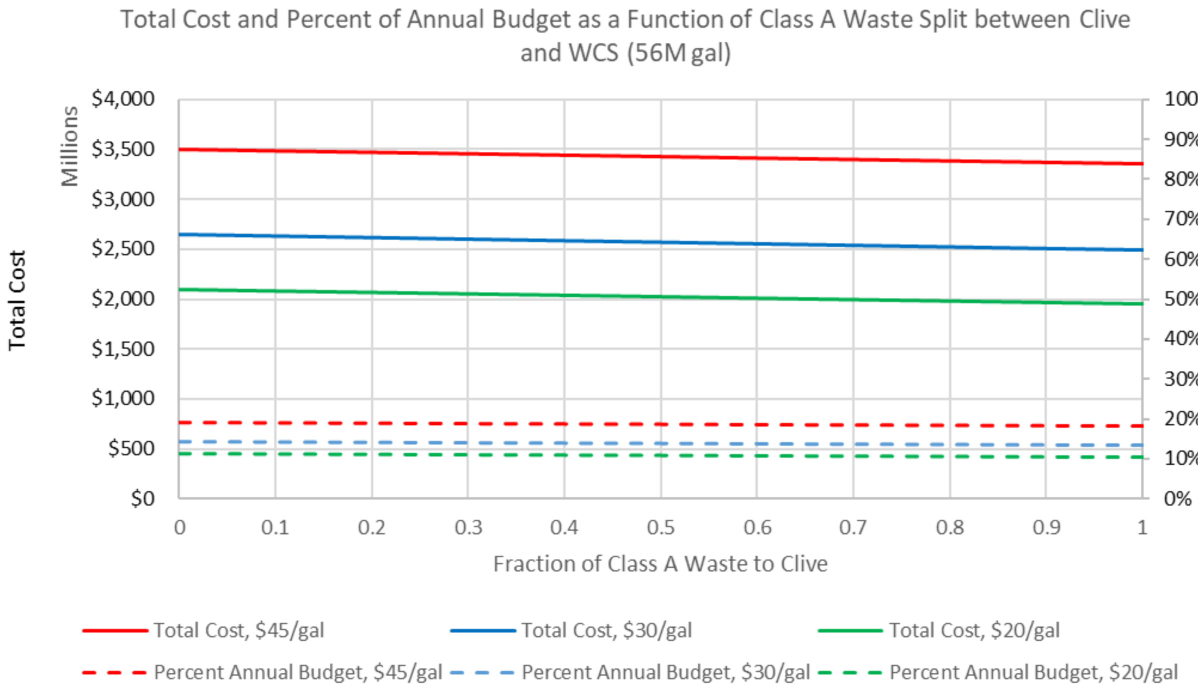

Figure D-12. Total Grout Disposal Cost and Percent Annual Budget, SP9 1B Feed Vector

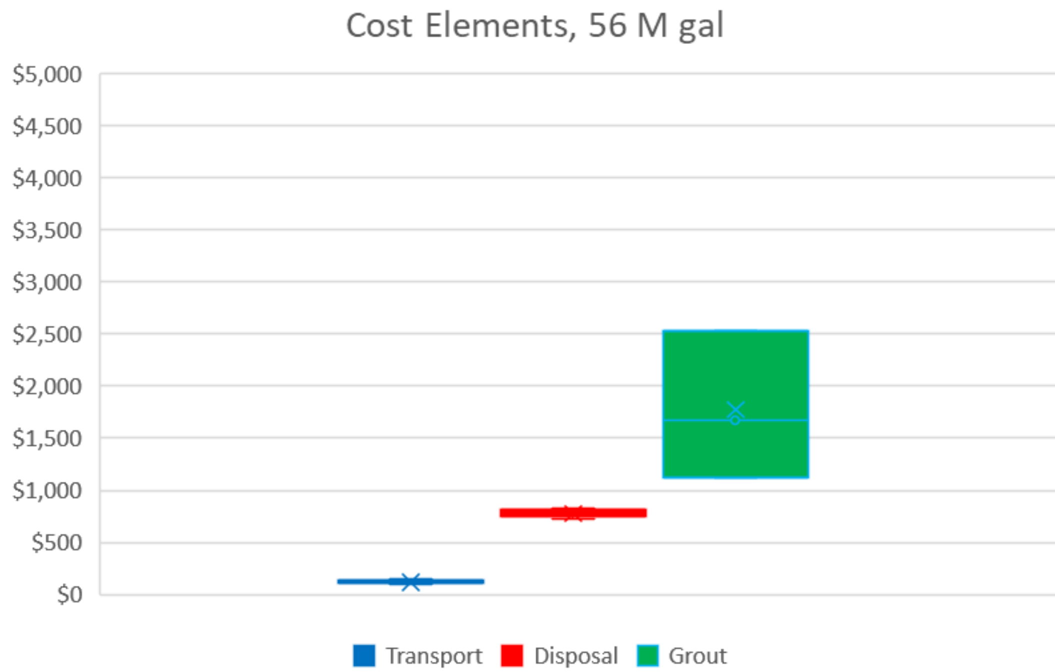

Figure D-13. Grout Disposal Cost Elements, SP9 1B Feed Vector

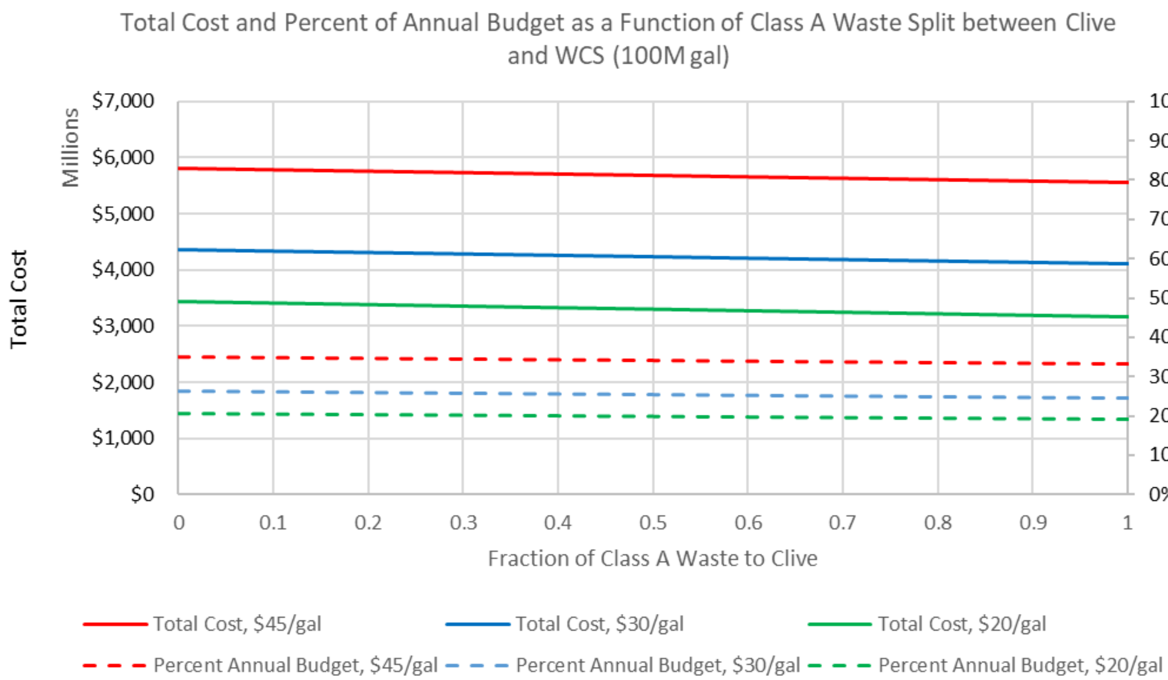

Figure D-14. Total Grout Disposal Cost and Percent Annual Budget, Early Start Feed Vector

Figure D-15. Grout Disposal Cost Elements, Early Start Feed Vector

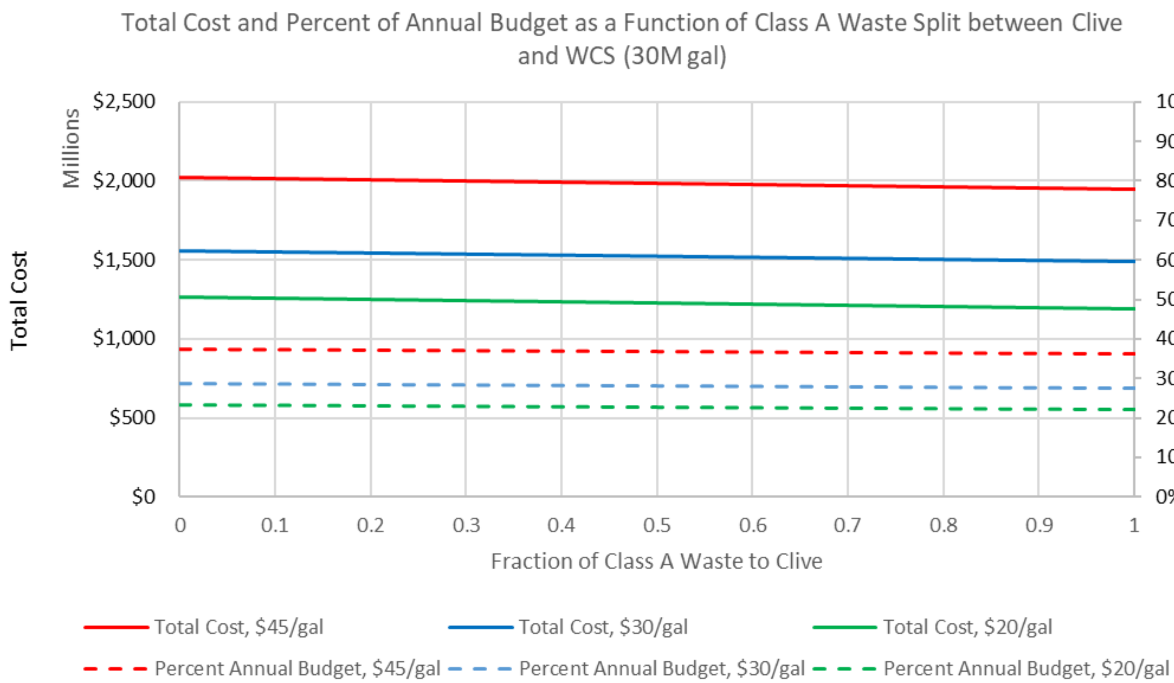

Figure D-16. Total Grout Disposal Cost and Percent Annual Budget, Early Start Feed Vector, Disposal until 2040

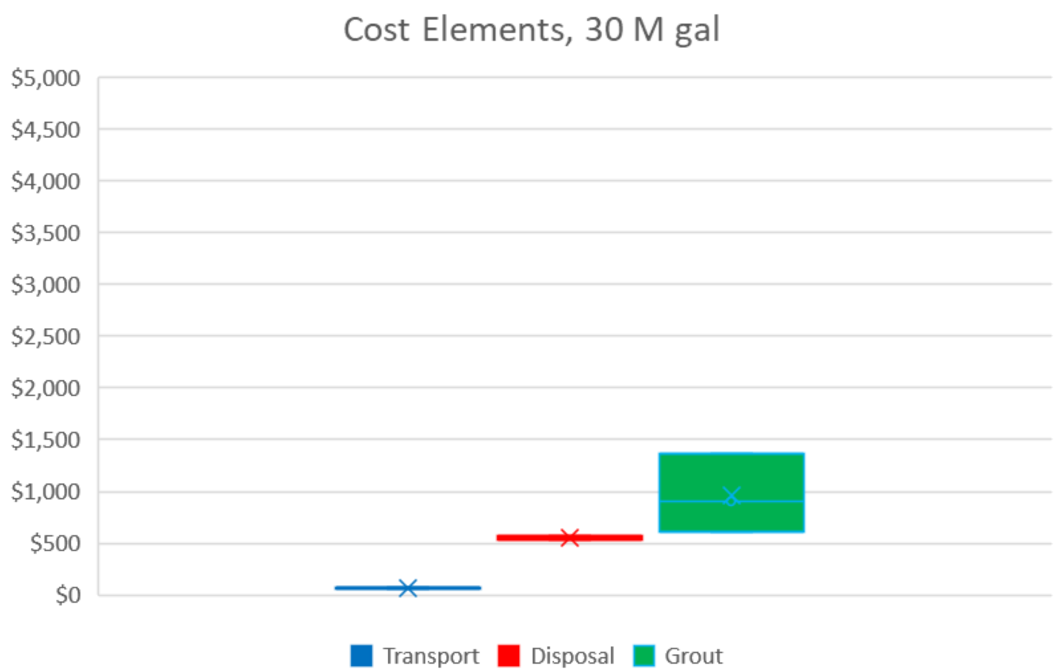

Figure D-17. Grout Disposal Cost Elements, Early Start Feed Vector, Disposal until 2040

Figure D-18 compares the total off-site transportation and disposal costs for grouted and FBSR waste forms. The costs of grout production are not included. The costs are similar in grout and FBSR cases with the SP9 1B feed vector. The grout with the Early Start feed vector has the highest cost and the grout with the Early Start feed vector with off-site disposal until 2040 has the lowest cost.

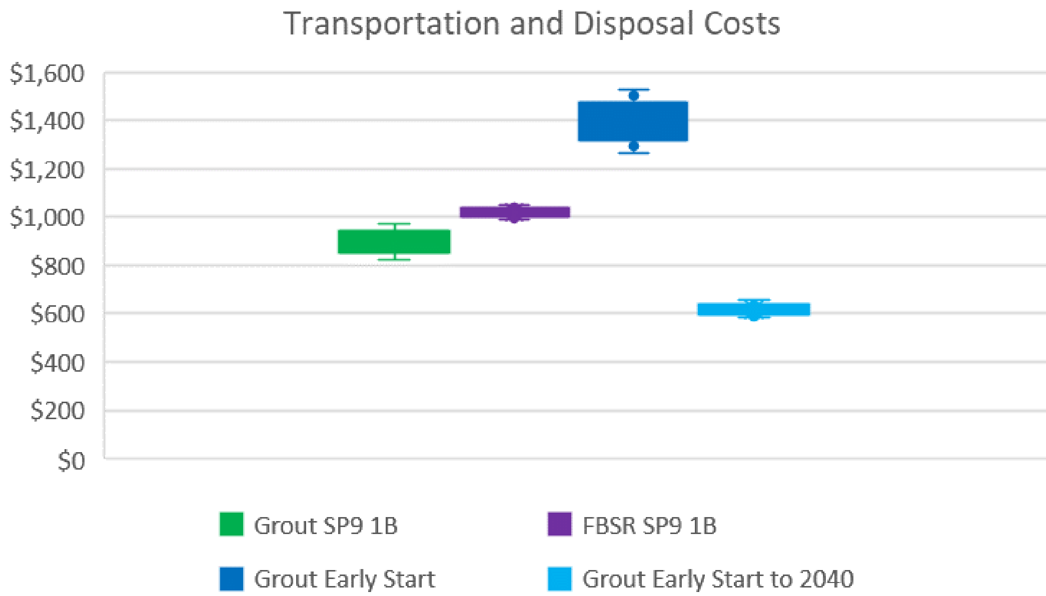

Figure D-18. Transportation and Disposal Costs

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).

That said, 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 potentially require the development of NEPA 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 analogues for risks for proposed shipping campaigns to WCS or Clive.

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 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 2 of Table H-2 of Volume II, Appendix H. 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 D-8.

Table D-8. 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

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. These were adjusted for rates from 2006 to 2016, resulting in an average of 1.0 fatalities occurred per million train-miles for the years 2006 through 2016. For a train from the Hanford Site to WCS, the roundtrip distance is 5,006 mi; assuming one train per month, a total of 60,000 train-miles per year, (statistically) would result in 0.060 fatalities per year and 2.52 fatalities over the full 42-year program. To put this impact (2.5 statistical fatalities in 42 years) in context, 42 years of baseline rail operations will result in 31,920 statistical fatalities 42 × 760). Stated differently, 2.5 statistical fatalities represent a 0.008% increase in rail fatalities over the 42-year program.

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.

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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 ensure 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 identify where the criteria are documented.

E.2 CROSSWALK

Table E-1. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

H.R. 6395[a] – 995 text	FFRDC Report Decision-Informing Criteria[b]
3125(c)(1)(A): The maturity and complexity of the technology	**3.1.1.2**: Process complexity **3.1.1.5**: Technology maturity
3125(c)(1)(B): The extent of previous use of the technology	**3.1.1.5**: Technology maturity
3125(c)(1)(C): The lifecycle costs and duration of use of the technology	**2.1**: Specific risks or benefits related to ongoing tank degradation **2.4**: Duration **3.2**: Likelihood and consequences of failing to complete due to resource constraints 4.: Lifecycle costs
3125(c)(1)(D): The effectiveness of the technology with respect to immobilization	1.: Long-term effectiveness **1.1**: Residual threat to health and environment upon successful completion
3125(c)(1)(E): The performance of the technology expected under permanent disposal	1.: Long-term effectiveness **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
3125(c)(3): The compliance of such approaches with the technical standards described in 3134(b)(2)(D) of the FY2017 NDAA[c] (i.e., CERCLA, RCRA, Clean Air and Clean Water Acts)	1.: Long-term effectiveness **1.1**: Residual threat to health and environment upon successful completion 5.: Securing and maintaining necessary permits and authorities
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	5.: Securing and Maintaining Necessary Permits and Authorities
3125(c)(5)(B): Public acceptance	6.: Community/Public Acceptance

Table E-1. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

H.R. 6395[a] – 995 text	FFRDC Report Decision-Informing Criteria[b]
3125(c)(5)(C): Cost	**3.2**: Likelihood and consequences of failing to complete due to resource constraints 4.: Lifecycle cost
3125(c)(5)(D): Safety	**2.2**: Risks to humans (other than tank degradation)
3125(c)(5)(E): The expected radiation dose to maximally exposed individuals over time	**1.2.2.1-1.2.2.3**: Confidence in immobilization with regard to groundwater **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.
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	**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	**3.1.1.5**: Technology maturity, MOE #2: Demonstrated effectiveness elsewhere (including Test Bed Initiative) and MOE #3: Analogous DOE experience
3125(c)(8)(C): Outcomes of the Test Bed Initiative of the Hanford Office of Environmental Management	**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] Additional information is provided in Volume I, Appendix A and Attachment A-1.
[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

Clean Air Act of 1972, 42 USC 7401 et seq.

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