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SPECIAL ANALYSIS FOR DISPOSAL OF HIGH-CONCENTRATION I-129 WASTE IN THE INTERMEDIATE-LEVEL VAULTS AT THE E-AREA LOW-LEVEL WASTE FACILITY

Prepared by:

Leonard B. Collard

January 7, 2000

Rev. 0

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

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SAVANNAH RIVER SITE

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LIST OF ACRONYMS & ABBREVIATIONS

3D	three dimensional
ρ_b	dry bulk density
ρ_s	particle density
ACRI	Analytical and Computational Research, Inc.
ALARA	as low as reasonably achievable
ANSI	American National Standards Institute
ARAR	applicable or relevant and appropriate requirement
ASL	above sea level
ASME	American Society of Mechanical Engineers
AT	advanced tensiometer
BNFL	British Nuclear Fuels Company
^oC	degrees Centigrade
CA	Composite Analysis
CAS	Computer Applications Specialist
cc	cubic centimeters
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CEWU	cement-stabilized encapsulated waste unit
CFR	Code of Federal Regulations
cfs	cubic feet per second
Ci	curie
Ci/y-Ci	curies per year per curies disposed
cm	centimeter
cm/y	centimeters per year
cpu	central processor unit
CSEW	cement-stabilized encapsulated waste
CRSA	Central Savannah River Area
+d	signifies that a radionuclide has potentially significant daughters
DCF	dose conversion factor
DCG	DOE Derived Concentration Guide
DOC	U.S. Department of Commerce
DOE	U.S. Department of Energy
D/Q	relative deposition
DWPF	Defense Waste Processing Facility (at the SRS)
DWS	drinking water standards
E	exponential notation (e.g., 5E-10 = 5×10^{-10} = 0.0000000005).
EDE	effective dose equivalent
EH	U.S. DOE Office of Environment, Safety, and Health
EIS	Environmental Impact Statement
EMOP	E-Area Monitoring Program
EPA	U.S. Environmental Protection Agency
^oF	degrees Fahrenheit
FACT	Flow and Contaminant Transport Model
FEMWASTE	Finite-Element Model of Waste Transport
FLASH	Finite Element Computer Code for Variably Saturated Flow
ft	feet
FY	fiscal year
g	gram
GSA	General Separations Area (at the SRS)

h	hour
HTO	tritiated water vapor
ICRP	International Commission on Radiological Protection
IL	intermediate level
in	inches
INEEL	Idaho National Engineering and Environmental Laboratory
K_d	sorption coefficient
K_v	vertical hydraulic conductivity coefficient
kg	kilograms
kg $m^{-2}yr^{-1}$	kilograms per square meter per year
km	kilometers
km^2	square kilometers
L	liters
LAW	low-activity waste
L/d	liters per day
LHS	Latin Hypercube Sample
LLD	lower limit of detection
LLW	low-level waste
LLWF	Low-Level Waste Facility
M	moles
m	meters
MAP	PA Maintenance Program
MCL	maximum contaminant level
MEXAMS	Metals Exposure Analysis Modeling System
μCi	microcuries
μg	micrograms
μS/cm	microsiemens per centimeter
mg	milligrams
mL	milliliters
MMI	Modified Mercalli Intensity
MPC	maximum permissible concentration
mrem	millirems
msl	mean sea level
nCi	nanocuries
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NQA	Nuclear Quality Assurance
NRC	U.S. Nuclear Regulatory Commission
NTU	nephelometric turbidity units
NWS	National Weather Service
ORNL	Oak Ridge National Laboratory
ORWBG	Old Radiological Waste Burial Ground (at the SRS)
PA	performance assessment
pc	personal computer
PCCG	Preconditioned Conjugate Gradient
pCi	picocuries
PI	principal investigator
PNL	Pacific Northwest Laboratory
QA	quality assurance
RAM	random-access memory
RCRA	Resource Conservation and Recovery Act

R&D	research and development
%ROI	percent region of influence
RPA	Radiological performance assessment
s. or **sec**	second
SA	Special Analysis
SAFT3D	Subsurface Analysis Finite Element Model for Flow and Transport in 3 Dimensions
SAR	Safety Analysis Report
SCDHEC	South Carolina Department of Health and Environmental Control
SDCF	scenario dose conversion factor
SMCL	Secondary Maximum Contaminant Level
SQA	software quality assurance
SQC	software quality control
SRS	Savannah River Site
SRTC	Savannah River Technology Center
SWD	Solid Waste Department of WSRC
$T_{1/2}$	halflife
TDR	Time-domain reflectometer
U.S	United States
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTR	Upper Three Runs
VAM3DCG	Variably Saturated Analysis Model in Three Dimensions with Preconditioned Conjugate Gradient Matrix Solvers
VZMS	Vadose zone monitoring system
WAC	waste acceptance criteria
WITS	Waste Information Tracking System
WQS	water quality standard
WSRC	Westinghouse Savannah River Company
X/Q	relative concentration
y or **yr**	year

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SECTION 1

EXECUTIVE SUMMARY

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1. EXECUTIVE SUMMARY

This Special Analysis (SA) addresses disposal of high-concentration I-129 wastes in the Intermediate Level (IL) Vaults at the Savannah River Site E-Area Low-Level Waste Facility. This SA addresses both the existing activated carbon vessels already placed in the IL Vault and any type of future waste that contains a high-concentration of I-129. An equation is developed that relates a waste form's vault inventory limit of I-129 to the waste form's measured K_d.

This SA was prepared to meet the requirements of the U.S. Department of Energy Order 435.1 (DOE 1999a). The Order specifies that a performance assessment or SA should provide reasonable assurance that a low-level waste disposal facility will comply with the performance objectives of the Order. The performance objectives require that:

- Dose to representative members of the public shall not exceed 25 mrem (0.25 mSv) in a year total effective dose equivalent from all exposure pathways, excluding the dose from radon and its progeny in air.
- Dose to representative members of the public via the air pathway shall not exceed 10 mrem (0.10 mSv) in a year total effective dose equivalent, excluding the dose from radon and its progeny.
- Release of radon shall be less than an average flux of 20 $pCi/m^2/s$ (0.74 $Bq/m^2/s$) at the surface of the disposal facility. Alternatively, a limit of 0.5 pCi/l (0.0185 Bq/l) of air may be applied at the boundary of the facility.

In addition to the performance objectives, the Order requires, for purposes of establishing limits on the concentrations of radionuclides that may be disposed of near-surface, an assessment of impacts to water resources and to hypothetical persons assumed to inadvertently intrude for a temporary period into the low-level waste disposal facility.

The E-Area Low-Level Waste Facility, located on a 200-acre site immediately north of the former low-level waste burial site (i.e., 643-7E), provides disposal capacity for solid, low-level, non-hazardous radioactive waste. This facility is planned to contain the following disposal units:

- two large concrete vaults for low-activity waste
- two large concrete vaults for intermediate-level non-tritium and tritium waste

- ten unlined trenches for disposal of soil and rubble with very low activity
- ten unlined trenches for disposal of intimately-mixed cement-stabilized waste
- ten unlined trenches for disposal of cement-stabilized encapsulated waste, and
- one gravel pad for disposal of up to 100 Naval Reactor Component waste containers.

This SA addresses disposal in the IL Vaults of a special category of wastes. These wastes contain high concentrations of I-129 and have measured, waste-specific desorption K_ds. K_ds represent the partitioning of contaminants between the solid waste particles and the liquid that can transport the contaminant. This SA analyzes the transport of radionuclides from the waste to the publicly accessible environment.

An important factor in estimating the transport of radionuclides to the environment at E Area is the long-term performance of the engineered features of the IL Vaults. Therefore, degradation of these features, including moisture barriers and concrete waste forms, is addressed in this SA.

To evaluate the transport of I-129 from materials with measured, waste-specific I-129 K_ds, site-specific conceptual models were developed to consider:

- exposure pathways and scenarios of potential importance
- potential releases from the facility to the environment
- effects of degradation of engineered features, and
- transport in the environment to a designated point of compliance.

For evaluation of doses to off-site members of the public and impacts on water resources, the point of compliance is the point of highest concentration in groundwater or air more than 100 m from the disposed waste. For evaluation of doses to inadvertent intruders, the point of compliance is located at the point of highest concentration of radionuclides after a 100-year institutional control period following closure of the facility.

This SA was used to determine the allowable I-129 inventories in the IL Vaults for materials with measured, waste-specific K_ds. Allowable I-129 inventory limits were calculated by comparing estimated groundwater concentrations with the Maximum Contaminant Level (MCL, see Section

4.2.2) and by comparing off-site and intruder doses with DOE Order limits on doses. Calculated inventory limits were also compared with the 10-year projected inventories for this type of waste.

The calculated inventory limits for activated carbon vessels of 7.14E-2 Ci (Section 5.1) exceed the 7.11E-2 Ci sum (Appendix A) of the existing and projected inventory for the existing IL Vault according to the performance evaluation conducted in this SA. This evaluation is based on the assumption that the entire IL Vault is filled with the waste being analyzed. Because the IL Vault will contain other wastes as well, appropriate adjustments are required when calculating the contribution from each waste to the total allowable doses.

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SECTION 2

INTRODUCTION

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2. INTRODUCTION

This Special Analysis (SA) addresses disposal of wastes with high concentrations of I-129 in the Intermediate-Level (IL) Vaults at the operating, low-level radioactive waste disposal facility (the E-Area Low-Level Waste Facility or LLWF) on the Savannah River Site (SRS). This SA provides limits for disposal in the IL Vaults of high-concentration I-129 wastes, based on their measured, waste-specific desorption K_ds.

2.1 Approach

This SA was developed using the U.S. Department of Energy's (DOE) Order 435.1, *Radioactive Waste Management*, supplemented where needed, by the interim guidance for performance assessment (PA) (DOE 1996). The interim guidance that clarifies performance objectives in DOE Order 5820.2A, was used because similar guidance for the new DOE Order is not yet available.

Several steps were taken to streamline this document while completely addressing all requirements. First, screening methodologies were applied where appropriate. Detailed evaluation of exposure scenarios in Section 6 was limited to those that provided the maximum exposure to individuals. Second, only general supporting information was provided, e.g. meteorological data and environmental information, and additional details were referenced. Third, the sister SA for Cement-Stabilized Encapsulated Waste (CSEW, DOE 1999b) was referenced where the information or analysis was very similar. The revised PA is the preferred reference but it is not yet available.

The level of technical detail presented in the report, together with the Appendices, is sufficient to allow a reviewer to reproduce the results of the SA calculations. Where appropriate, intermediate results are provided. For example, the flux of each radionuclide to the water table, which is an intermediate result in the calculation of groundwater concentrations at the point of compliance, is presented in tables and plots. The Appendices include detailed supporting information.

2.2 General Facility Description

The E-Area LLWF is the site selected to store and dispose of all low-level radioactive waste generated during at least the next 20 years of SRS operations. The E-Area LLWF site is located on a 200-acre site immediately north of the former LLW burial site. Only 100 acres of the E-Area LLWF have been developed at this time (Fig. 2.2-1); the additional 100 acres will allow for expansion of LLW disposal capacity as needed. The nearest SRS boundary to the E-Area LLWF is about 11 km to the west. The E-Area LLWF is in a relatively level highland region of SRS at about 90 m (300 ft) above msl.

The E-Area LLWF is designed to provide containment to reduce radionuclide migration from disposed LLW forms. Low-level waste will be disposed in trenches, concrete vaults, and on waste pads. The concrete vaults include Low-Activity Waste (LAW) Vaults and Intermediate-Level (IL) Vaults. Trench disposal includes rubble and miscellaneous wastes, intimately mixed cement-stabilized waste forms (e.g., ashcrete and blowcrete from the Consolidated Incinerator Facility), and cement-stabilized encapsulated waste (CSEW). The waste pads hold naval reactors. As current disposal units near capacity, additional disposal units will be constructed if needed.

2.2.1 High-Concentration I-129 Waste Disposal in Intermediate-Level Vaults

2.2.1.1 Description and Location

IL Vault locations within the E-Area LLWF are shown in Fig. 2.2-1. Each IL Vault is subdivided into an Intermediate-Level Non-Tritium (ILNT) Vault and an Intermediate-Level Tritium (ILT) Vault. The ILT Vault will be used for disposal and storage of tritium-bearing waste, packed in 10-gallon drums, or spent tritium extraction crucibles from which almost all the tritium has been removed, and tritium job control waste (JCW).

The ILT Vault and the ILNT Vault are similar in design. The ILT Vault is structurally identical to the ILNT Vault, except for length and depth. The ILT Vault consists of two cells or subdivided sections within the vault structure and provides approximately 1.6×10^3 m^3 (56,000 cubic feet) of

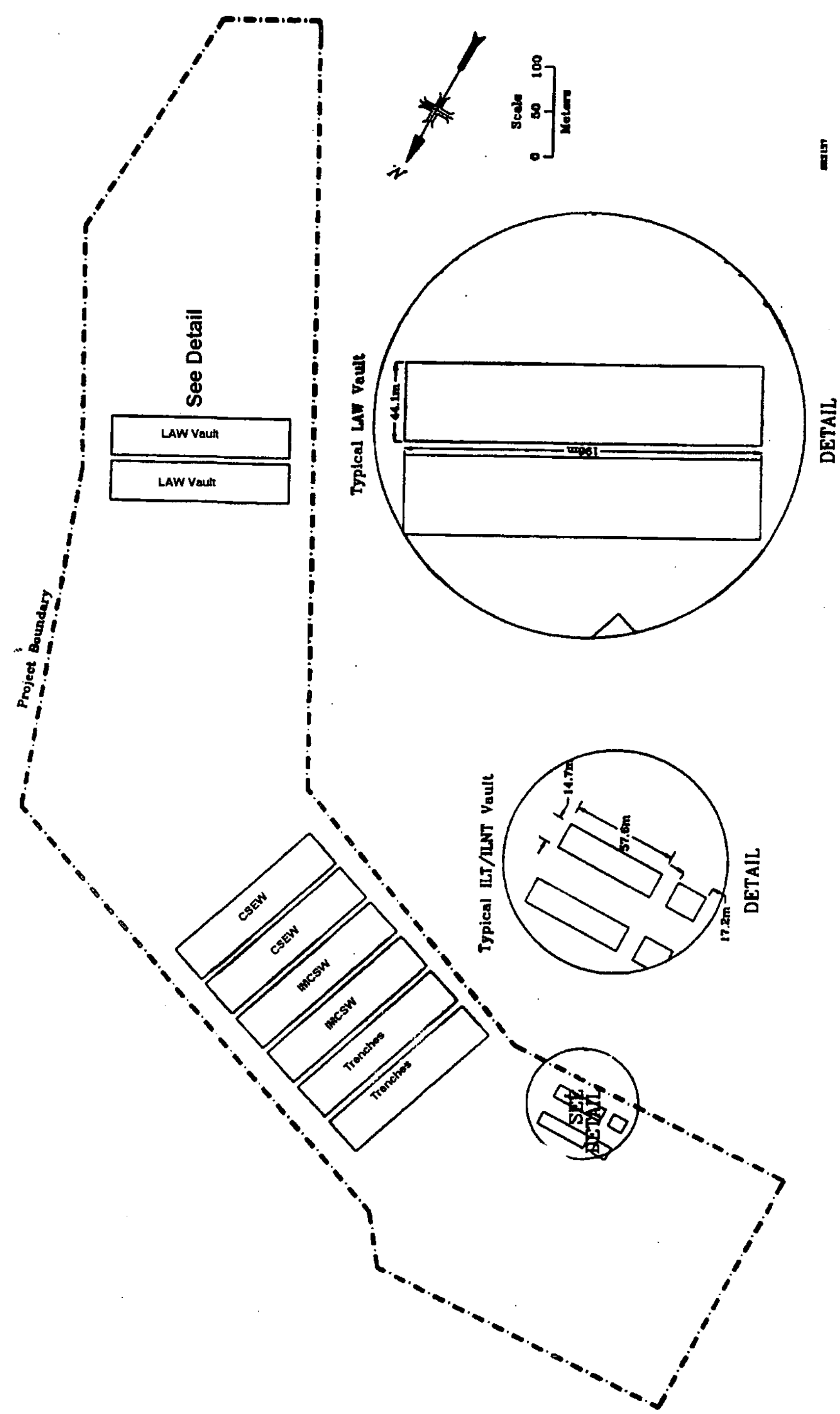

Figure 2.2-1 Projected Layout of the E-Area Low-Level Waste Facility

waste disposal capacity (Fig. 2.2-2). As originally conceived, one cell in the ILT Vault is fitted with a silo system to permit the disposal of tritium crucibles. The ILNT Vault consists of seven cells within the vault structure and provides approximately 5.7×10^3 m^3 (approximately 200,000 cubic feet) of waste disposal capacity (Fig. 2.2-2). The base of the IL Vault is at an average elevation of 78 m (260 ft) above msl. Both the ILT Vault and the ILNT Vault use the same crane for waste container handling, they are immediately adjacent and are closed as a single unit.

2.2.1.2 Major Design Philosophy

Specific design measures were applied to the IL Vault to enhance safe operation, as described below:

1) Water Removal Provisions - The floor of each cell slopes to a drain that runs to a sump in the base slab. Any water accumulating in the sump can be monitored and removed through a 0.15-m diameter riser pipe at the top of the wall. Any water that collects under the vault will flow to dry wells between the ILNT Vault and the ILT Vault. Access to the dry well is through a manhole at grade level.

   Each cell has a removable metal rain cover consisting of a steel truss with a metal deck. The roof of the rain cover slopes slightly away from the center to allow water drainage. A crane is used to place the rain cover over the cell when the cell is not operating.

   All concrete joints include a waterstop seal that is continuous around all corners and intersections. All exterior concrete surfaces exposed to soil are coated with tar-based waterproofing.

2) Radiation Shielding – Each cell can be covered with reinforced concrete slabs, known as shielding tees, to reduce the radiation level at the edge of the vault. The profile of these slabs is in the shape of the letter "T" so that they can be interlocked to provide 0.5 m of shielding.

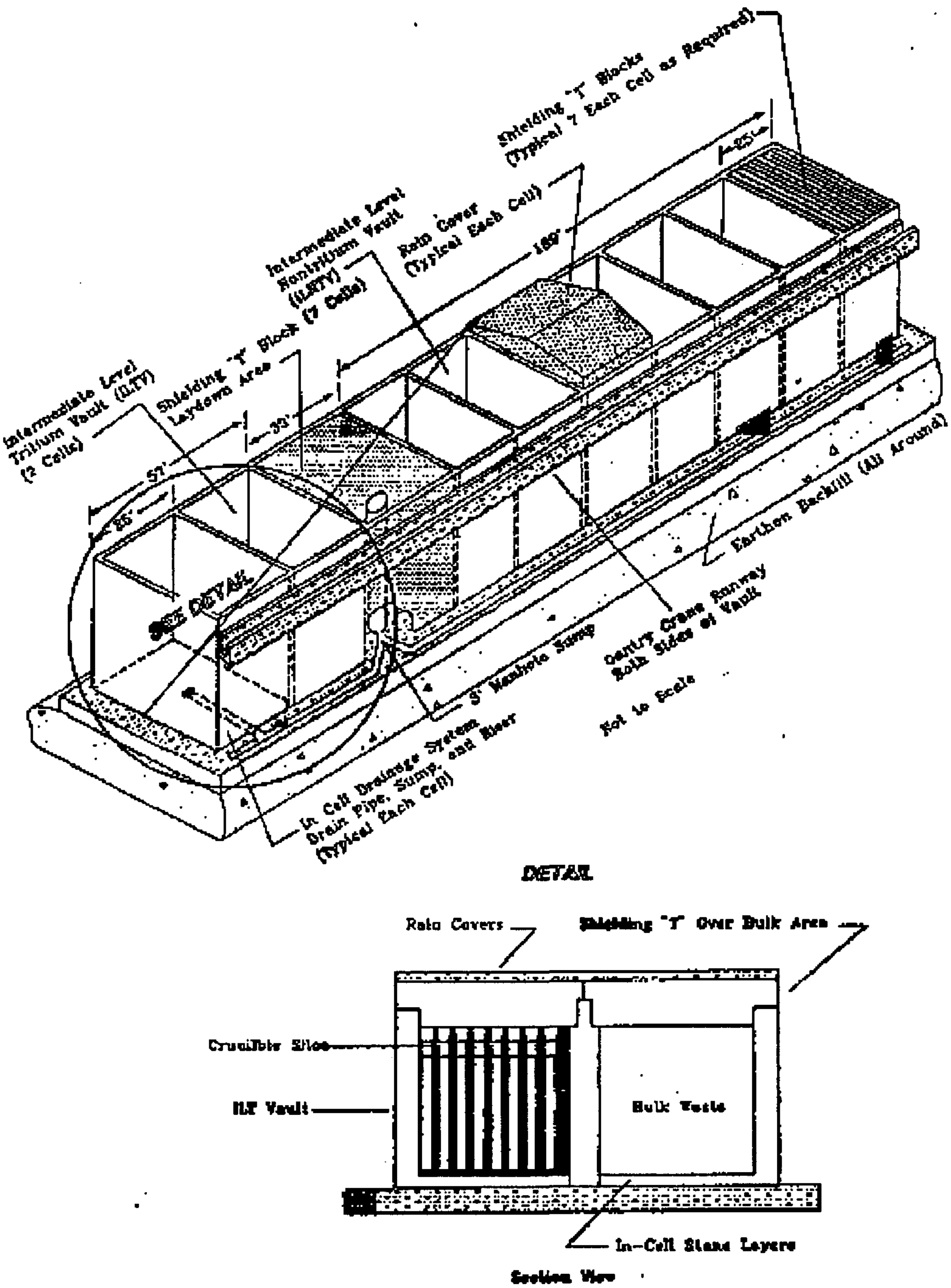

Figure 2.2-2. Arrangement of the Intermediate Level Non-Tritium and Intermediate Level Tritium Vaults

The IL Vault is classified as a Hazard Category 3 Facility (WSRC 1996a). However, the vaults were designed to meet the requirements of a Maximum Resistance (High Hazard) structure during the interim and final closure phases. The IL Vault satisfies the criteria for classification as a Standard Resistance (General Use) Structure.

As documented in the Structural Design Criteria (S2889-306-25-0) the IL Vault was designed and constructed to be a maximum resistance structure after closure. Site Specification 7096 requires that a maximum resistance structure be designed to withstand a 0.2 g earthquake event.

Each IL Vault has three distinct phases of operation and closure as follows:

1) Operating Phase – This phase involves waste emplacement. As each layer of waste containers is completed, grout is poured around and over the containers to form a new working surface for emplacement of the next layer.

2) Interim Closure Phase – After the final layer of waste containers is placed into the cell, a final layer of grout is placed in the cell and is leveled at the wall ledges that support the shielding slabs. A permanent roof slab of reinforced concrete is placed over the nine IL Vault cells. The roof slab is covered with fiberboard and a layer of waterproof membrane roofing.

3) Final Closure Phase – This phase will be performed after all vaults are interim-closed. Final closure consists of placing an earthen cover with an engineered clay cap over the entire E-Area LLWF.

2.2.1.3 Facility Features

The ILNT Vault is a below-grade, reinforced concrete structure approximately 58 meters (189 feet) long, 15 meters (48 feet) wide, and 9 meters (29 feet) deep with a seven-cell configuration (see Fig. 2.2-2). Exterior walls are 0.76 meters (2-1/2 feet) thick; and interior walls forming the cells are 0.46 meter (1-1/2 feet) thick. Walls are structurally mated to a base slab that is approximately 0.76 meter (2-1/2) thick and extends past the outside of the exterior walls approximately 0.6 meter (2 feet). The base slab is supported on two layers of crushed stone placed on a compacted subgrade.

Concrete construction joints are located at defined control joints, with no horizontal joints in any vertical wall.

The ILT Vault consists of two cells with a combined length of approximately 17 m (57 ft). One cell is identical to the ILNT Vault cells. The other ILT Vault cell is 0.6 m (2 ft) deeper and has been fitted with a silo storage system designed to house tritium crucibles (see Fig. 2.2-2). This cell is equipped with 142 silos, for tritium crucibles and tritium reservoirs. The crucibles are contained in overpacks. After a crucible has been placed in a silo, a 1-m thick shielding plug is installed to reduce radiation exposure from the disposed crucible.

One IL Vault has been constructed, consisting of one ILNT vault and one ILT vault. It is assumed that future IL vault construction will be identical to the existing IL Vault - a combined single-vault configuration of nine cells housing both ILT and ILNT waste.

2.2.1.4 Waste Characteristics

ETF and ER operations at SRS produce materials with relatively high concentrations of I-129. Because these materials concentrate I-129 from water, they are likely to retain the I-129 longer than other materials and to release it more slowly. The I-129 release rate from each material is calculated from the desorption solid-water partition coefficient (K_d), where that coefficient represents the partitioning of contaminants between the solid waste particles and contacting liquid.

Desorption K_ds for these materials were measured in the laboratory and input to numerical models. Measured K_ds higher than the literature-based value of 30 ml/g indicate slower release rates that translate into lower groundwater concentrations and lower doses to the public.

The ETF materials that contain high concentrations of I-129 are GT-73 resin and Activated Carbon Vessels. The ER materials are sludge/filtercake, Dowex 21K resin, and zeolite. Current plans are to dispose of only the Activated Carbon Vessels in the IL Vaults. Four Activated Carbon Vessels have already been placed in the existing IL Vault and grouted in place.

2.2.1.5 Disposal Concept Considerations and Movement of Waste Through the Facility

During the Operating Phase of the IL Vault, IL solid wastes are divided into tritium and non-tritium bearing fractions, and are disposed of separately in the ILT Vault and ILNT Vault, respectively. When a vault is being filled with waste, a crane removes the rain cover from the designated cell and any T-blocks that are installed over the designated cell. The crane transfers waste from the waste transport vehicle into the cell.

Waste containers placed in an IL vault cell are periodically encapsulated in grout. Successive grout layers are cured before installing additional waste containers. After waste placement and grouting operations (as needed) are completed, T-blocks are reinstalled and rain covers are replaced.

The Interim Closure Phase commences after the final waste is placed in the IL Vault. A final layer of grout will be placed in each cell and leveled at the wall ledges that support the T-blocks. A permanent roof slab of reinforced concrete will be installed that completely covers the vault cells.

The Final Closure Phase completes the closure by placing an earthen cover with an engineered clay cap over the entire vault area.

Operation of the ILT Vault is similar to that of the ILNT Vault. The ILT Vault receives tritium-bearing waste, packed in either crucibles or 10-gallon containers, and tritium JCW. A permanent roof slab is installed at the start of interim closure.

The crucible-silo system is designed to receive overpacked tritium waste containers. Each crucible is approximately 46 cm (18 in) in diameter and 6.1 m (20 ft) long. The silo system consists of approximately 142 50-cm- (20-in-) diameter cylinders, uniformly placed and aligned to form a vertical grid. Each silo is provided with a separate concrete shielding plug. The ILT Vault cell operation is the same as that described for the ILNT Vault except that T-blocks are not required for ILT Vault cells containing the silo system, because the shielding plugs provide radiation shielding.

2.2.1.6 Waste Acceptance and Certification

All LLW is subject to the Waste Acceptance Criteria (WAC) of the 1S Procedure Manual (WSRC 1999b). The 1S Manual procedure, WAC 2.02, *Low Level Waste Characterization Requirements*, provides requirements associated with the development of suitable methods for characterization of waste packages. This procedure establishes the basis to ensure that all LLW packages presented to Solid Waste for treatment, storage, or disposal have been characterized by the generator to reasonably represent the physical, chemical, and radiological contents of the waste package with sufficient accuracy to permit proper segregation, treatment, storage, and disposal.

According to procedure WAC 2.02, generators must periodically validate the radionuclide content and distribution in their waste streams after their initial certification. The purpose of periodic validation is to demonstrate that the waste stream distribution of the important radionuclides (i.e., those constrained by the WAC) has not changed significantly. The radionuclide content and distribution of all routinely generated SRS waste streams shall be reviewed and validated at least every two years.

The SRS certification procedure requires the generator to characterize the waste using laboratory analysis of representative samples. The procedure also requires that a facility sampling plan be used that ensures that samples are representative of the contaminated waste stream and are consistent and appropriate for each waste stream. After sample analysis results are screened, the remaining data shall be evaluated to consider:

- radionuclides identified in the data set compared to historic data sets, and reported values compared to historic sample data for the same waste stream,
- comparisons between in-house analysis results (if available) and independent laboratory results,
- scaling factor ranges relative to similar waste streams and historic data, and
- consistency of specific radionuclide results with gross analysis results.

The procedure indicates that characterization by means of sampling and analysis is the preferred method where it can be used. However, some waste streams cannot be adequately characterized through use of sampling and analysis techniques; therefore, process knowledge is appropriate and necessary.

Process knowledge includes the physical, chemical, and radiological properties of the materials involved in the process that generates the waste, the effect of all aspects of the process on the materials, associated process stream and product specifications, and administrative controls. Sources of process knowledge include historical operating and inventory records, analysis results, direct assay results, technical reports, documents and drawings specifying process areas and equipment, process equipment manuals, process stream or product specifications, documented mass balance information, and procedures. A radioisotopic distribution for a waste stream determined by process knowledge shall be validated using sampling and analysis of representative waste stream samples.

Materials of the same type are assumed to have the same I-129 desorption K_d, e.g., all activated carbon from Activated Carbon Vessels is assumed equal. However, the K_d has been shown to decrease as the concentration increases. If the I-129 concentration for any vessel is significantly higher than for the material that was measured, then further testing is needed or adjustments in disposal quantities are required.

2.2.1.7 Land Use Patterns

As described in Section 3.1.1.4, the use of land adjacent to the SRS is primarily rural.

2.3 Schedules

2.3.1 Operation/Waste Receipt

At this time, one IL Vault has been constructed. The next IL Vault will be constructed when needed based on future site activities.

2.3.2 Closure/Post-Closure

The entire E-Area LLWF will be closed after it serves its useful life that is expected to last for at least 20 more years.

2.4 Related Documents

The information in this section is identical to that in Section 2.4 of the CSEW report (DOE 1999b), except that the CSEW report is also related to this document.

2.4.1 Special Analysis for Disposal of Cement-Stabilized Encapsulated Waste at the E-Area Low-Level Waste Facility

The performance of the Cement-Stabilized Encapsulated Waste trenches was assessed in the CSEW Special Analysis (DOE 1999b). That report indicated that the projected inventories for ^{99}Tc and ^{129}I would exceed the calculated limits. Interaction of plumes from the CSEW and from high-concentration ^{129}I in the IL Vaults could produce concentrations higher than concentrations at the 100-m well thus requiring lower vault limits than those presented in Section 5. Plume interaction was not analyzed in either the CSEW report or in this report.

2.5 Performance Criteria

The information in this section is identical to that in Section 2.5 of the CSEW report (DOE 1999b). The exception is that the agriculture inadvertent scenario in this report starts at 20,000 years, because waste excavation for a basement is not credible until then.

2.6 Summary of Key Assessment Assumptions

For protection of the public and assessment of impacts on water resources, exposure pathways involving direct ingestion of groundwater are the pathways of dominant concern for this SA (see Section 4). For protection of intruders, the agricultural scenario dominates. It yields doses that are about a factor of 10 greater than the post-drilling scenario and about a factor of 30 greater than the residential scenario (Table C.3-17).

Assumptions of greatest importance to the projection of groundwater concentrations are those that affect the projection of release from the waste forms and subsequent transport to the point of compliance. Release from the waste forms is a strong function of the amount of water infiltrating to the disposal unit, the manner in which radionuclides are bound to waste, physical/chemical sorption properties of individual radionuclides, solubility of radionuclides, and the presence of engineered barriers to water flow.

The amount of infiltrating water and hydraulic properties of the soil matrix are important to the estimation of transport to the water table. However, for failed concrete, over long time periods when steady-state conditions are approached, hydraulic properties become less important, because the flow rate becomes controlled by the rate at which water infiltrates to the waste zone. Ultimately, groundwater concentrations are a function of the rate at which radionuclides reach the water table (affected by the parameters listed above) and of the parameters affecting transport through the aquifer.

Simulation of important release and transport processes requires a number of generally simplifying assumptions. Major assumptions that affect the predicted groundwater concentrations include:

1) moisture barriers (caps) are assumed to fail as soon as vaults fail, at 1,050 years
2) sorption is assumed to be adequately represented by non-site-specific sorption coefficients (K_ds) for many radionuclides and materials, although waste-specific sorption coefficients are required for the high-concentration I-129 wastes
3) I-129 is assumed to exist as surface contamination available for transport
4) the volume of cells in the simulation domain used for the groundwater transport simulations is assumed to be adequately small to avoid introducing unrealistic dilution of the radionuclides after reaching the water table, and
5) the volume of cells is small enough such that numerical dispersion does not introduce unrealistic dilution of the radionuclides in the simulations. Numerical dispersion occurs when a grid element in a numerical model is larger than the distance a molecule may travel by advection in one time step of simulation.

Assumptions of greatest importance to the estimation of dose resulting from release of volatile radionuclides to air have to do with the rate at which volatile radionuclides are released to the atmosphere and the time at which the releases occur.

For estimation of dose to inadvertent intruders, exposure scenario definitions (assumptions) are perhaps most critical to the SA. Probably the most important assumptions are: 1) the inadvertent intruder has no knowledge of prior waste activities at the site; 2) the intruder will build a home or drill a well at the location of disposal units, rather than in uncontaminated areas; 3) the intruder excavates or drills at the earliest time possible relative to degradation estimates for the various materials; and 4) exhumed waste is mixed with uncontaminated soil, and a garden is planted in the resulting mix. These important assumptions tend to maximize calculated dose to the intruder and thus provide a pessimistic evaluation of performance of the facility with respect to impacts on intruders.

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SECTION 3

DISPOSAL FACILITY CHARACTERISTICS

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3. DISPOSAL FACILITY CHARACTERISTICS

3.1 Site Characteristics

Site characteristics for high-concentration I-129 waste in the IL Vaults are identical to those for cement-stabilized encapsulated waste trenches at the E-Area LLWF. Thus, Section 3.1 in DOE, 1999b provides the needed site characteristics information for this SA. The only difference is that the seismic events could crack the vaults, rather than the encapsulating material.

3.2 Principal Facility Design Features

A key objective for closure of a waste disposal site is to limit moisture flux through the waste, thus minimizing contamination of the underlying groundwater. Because the E-Area LLWF is designed as a controlled release facility, proper closure to meet the objective of limiting moisture flux through the waste will be an integral part of long-term acceptability of the disposal site. Backfilling and final closure of the E-Area LLWF will be delayed for several years, hence a detailed closure design has not been fully developed. A closure concept must be described and tested in models that simulate its performance characteristics.

3.2.1 Intermediate-Level Vault Closure Concept

3.2.1.1 Water Infiltration and Disposal Unit Cover Integrity

Each IL Vault will be closed in stages. Individual cells will be closed as they are filled then the entire vault area will be closed. Final closure consists of placing an earthen cover with an engineered clay cap over the entire vault area. This closure activity will be combined with construction of a drainage system and revegetation using bamboo.

The closure concept developed for this SA is illustrated in Fig. 3.2-1. Closure operations begin when an individual cell is filled with waste. The concrete roof of the vault will be installed by tying its reinforcing steel into the reinforcing steel of the vault itself, forming a unified structure. Backfill will be placed around and over the disposal units after all vaults and trenches have been filled, although backfilling may begin slightly earlier.

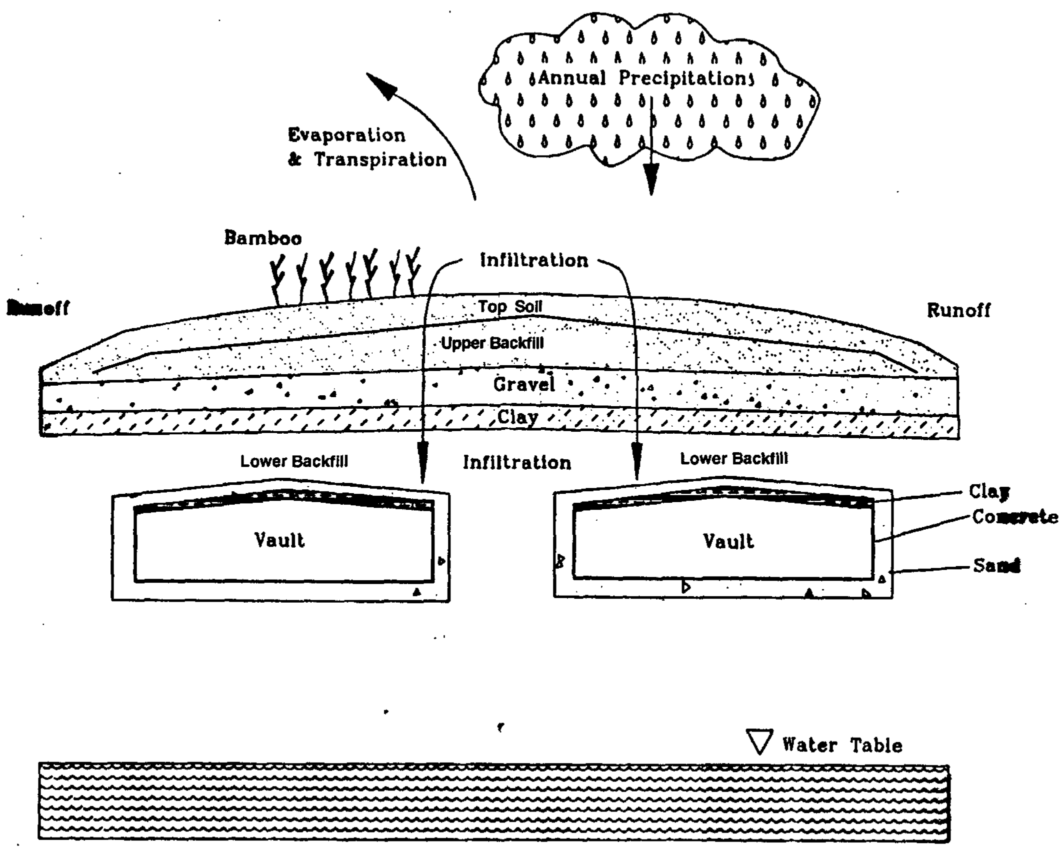

Figure 3.2-1. Vault closure concept (intact cover system)

At least 0.9 m of backfill will be placed over the vaults. This layer will serve to establish slopes for the overlying layers so that infiltrating water will tend to flow down the slope and away from the vaults, limiting the amount of infiltration into the vaults themselves. Above this layer of backfill, a laterally extensive moisture barrier will be installed. This moisture barrier will consist of 0.76 m of clay and an overlying layer of 0.3 m of gravel. A geotextile fabric will be placed over the gravel layer, and a second backfill layer, approximately 0.76-m thick, will be placed over the moisture barrier. Finally, a 0.15-m layer of topsoil will be placed over the top backfill layer. This sequence of layers provides a minimum of 2.9 m of cover for each vault.

Final closure of the E-Area LLWF will be accomplished by constructing a drainage system and revegetating the site. The drainage system will consist of a system of rip-rap lined ditches that intercept the gravel layer of the moisture barrier. These ditches will divert surface runoff and water intercepted by the moisture barrier away from the disposal site. The drainage ditches will be constructed between rows of vaults and around the perimeter of the E-Area LLWF.

The topsoil will be revegetated with bamboo. A study by the USDA Soil Conservation Service (Salvo and Cook 1993) has shown that two species of bamboo (Phyllostachys bissetii and Phyllostachys rubromarginata) will quickly establish a dense ground cover that prevents the growth of pine trees, the most deeply-rooted naturally-occurring plant type at SRS. Bamboo is a shallow-rooted climax species that evapotranspirates year-round in the SRS climate, thus, removing a large amount of moisture from the soil and decreasing infiltration into the underlying disposal system.

Performance requirements for the closure concept are expressed in terms of hydraulic properties for the various soil layers (Thompson 1991). These nominal properties are listed in Table 3.2-1. The topsoil and upper backfill layer serve to store and distribute infiltrating water. These layers intercept incoming water and redirect a significant portion in the horizontal direction to drainage ditches installed at the E-Area LLWF. Computer simulations of flow through the cover show that the gravel drainage layer will carry away a major portion of the water that would normally infiltrate at the E-Area LLWF (40 cm/yr).

Table 3.2-1 Values for hydraulic properties of vault closure design

Layer Description	Hydraulic Conductivity (cm/s)
Clay	1.0×10^{-7}
Gravel	0.5
Backfill	1.0×10^{-5}

3.2.1.2 Structural Stability and Inadvertent Intruder Barrier

The IL Vaults include features that promote structural stability as follows:

- The vaults are below-grade reinforced concrete structures. All walls are structurally mated to 2.5-foot thick concrete base slabs that extend approximately 2 feet beyond the outside of the exterior walls. The vaults are designed to withstand loads imposed by Design Basis Accidents and therefore, assure continued structural stability.

- Waste is placed in engineered metal containers before being brought to the vault. The containers are stacked in layers. After a layer of waste containers is placed in a cell, grout will be poured to encapsulate the containers and form a surface for emplacement of the next layer of containers.

- After being filled with waste and layers of grout, the vault will be covered with a top layer of grout. A thick (thickness varies from 2-feet – 3inches to 3-feet – 2 inches) reinforced- concrete roof slab will completely cover all nine cells of the IL Vault. The roof slab will extend over and around the cell-wall stubs and will be covered with a bonded-in-place layer of fiberboard insulation and a layer of waterproof membrane roofing. Structural stability of the IL vault roof is expected for about 1,050 years (Appendix D). The roof and grout layer provide a barrier both to water infiltration and to intrusion before that time.

Confinement features for the IL tritium portion of the IL vault are the same as the ILNT portion. One ILT cell is identical to ILNT cells. The other ILT cell contains silos for disposing of tritium crucibles in silos. The silo system consists of vertical cylinders that are grouted in place, thus providing stabilization and shielding.

3.3 Waste Characteristics

Low-level radioactive solid waste may be segregated by the Waste Generator into eight categories. The disposition of waste containers in the E-Area LLWF is based on this segregation. The waste categories are as follows:

1) Low-activity waste

2) Intermediate-level tritium waste

3) Intermediate-level non-tritium waste

5) E-Area trench waste

6) Naval Reactor Components

7) Intimately-mixed cement-stabilized waste

8) Cement-stabilized encapsulated waste

This SA addresses a sub-category of the Intermediate-level not-tritium waste, namely waste with a high I-129 concentration.

3.3.1 Intermediate-Level Vaults

3.3.1.1 Waste Type/ Chemical and Physical Form

The IL Vault will be used for disposal of IL waste. IL waste is defined at SRS as waste radiating greater than 200 mR/hour at a distance of 5 cm. Intermediate-level waste consists of job control waste (JCW), scrap hardware, contaminated soil and rubble, and wastes in non-standard containers. IL JCW is primarily highly contaminated lab coats, plastic suits, shoe covers, plastic sheeting, etc. JCW is typically combustible and is contaminated primarily with fission products. Scrap hardware waste consists of reactor hardware, reactor fuel and target fittings, jumpers, and used canyon and tank farm equipment contaminated with fission products and/or induced activity. Contaminated soil and rubble result from cleanup and decommissioning operations. Wastes in non-standard containers are those that normally could be disposed in the LAW vaults, but the size or shape of the container prevents that means of disposal.

All IL waste will be packaged in engineered metal or concrete containers that have been approved by Solid Waste Management. The containers will be remotely placed into the vault in layers. IL waste containers will be grouted in place to provide better waste isolation, reduce dose to operators, and improve stacking of additional containers.

3.3.1.2 Radionuclide Inventory

The 10-year projected inventory of high-concentration I-129 waste for the IL Vaults is provided in Appendix A.

3.3.1.3 Waste Volume

The IL vault provides approximately 5.7×10^3 m^3 of waste capacity for ILNT waste and 1.6×10^3 m^3 for ILT waste (Section 2.2.1.1). If disposal limits are not exceeded, waste volumes may approach that capacity for both IL vaults during the period of operation of these units.

3.3.1.4 Packaging Criteria

All LLW is subject to the packaging requirements of the 1S Manual. Most LLW will be received in standard $1.2 \times 1.2 \times 1.8$ m (2.5 m^3) metal containers (B25 boxes). Some waste will also be received in standard $0.6 \times 1.2 \times 1.8$ m (1.3 m^3) containers (B12 boxes) or 210-L (55-gallon) drums. The LLW may also be received in non-standard engineered concrete or metal containers. These containers shall be pre-approved by Solid Waste Management prior to their receipt at the E-Area LLWF.

Many different containers will be received at the E-Area LLWF. However, all containers are required by the Technical Safety Requirements (TSRs) to be engineered concrete or metal containers that have been approved by Solid Waste. Solid Waste verifies that the container can be safely handled, will not impair vault space utilization, and will satisfactorily contain the waste contents.

B25 and B12 carbon-steel boxes have been used in the past for waste disposal in the SWDF. The boxes are similar in construction, differ in size. The B25 is typically constructed of 14-gauge carbon steel (1.9 mm) but some B25s are constructed of 12-gauge carbon steel (2.6 mm) to allow use in the compactor. The B12 is typically constructed of 12-gauge carbon steel.

3.3.1.5 Pre-Disposal Treatment Methods

No pre-disposal treatment methods are currently planned for IL waste.

3.3.1.6 Waste Acceptance Restrictions

Waste acceptance for disposal in the IL vaults must conform to criteria put forth in the SRS WAC (WSRC 1999b).

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SECTION 4

ANALYSIS OF PERFORMANCE

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4. ANALYSIS OF PERFORMANCE

The methods used to analyze the long-term performance of the high-concentration I-129 waste in the IL Vaults are described in this chapter. Source term development is addressed in Section 4.1, where a discussion of potential mechanisms of contaminant release from the disposal units is provided. In that section, the screening process used to identify potentially significant radionuclides for different analyses is also described.

In Section 4.2, potentially significant exposure pathways and scenarios for off-site members of the public are described. Screening pathways and scenarios are also discussed in this section, as are receptor locations for subsequent analysis.

Finally, in Section 4.3, the conceptual models developed to analyze the fate and transport of I-129 released from the high-concentration I-129 wastes in the IL Vaults for the pathways identified in Section 4.2 are described. Computational methods used to evaluate the models are also discussed.

4.1 Source Terms

In this section, mechanisms and factors that affect the rate of potential release of radionuclides from the IL disposal units to the environment are discussed. Screening techniques used to focus analyses on significant processes are also described. After significant processes are identified, conceptual models for release from waste forms and disposal units are presented. These models address releases from initially intact disposal units and releases from units after degradation of engineered barriers has occurred. Simulation models and assumed values of model parameters are discussed. Calculated releases to the environment over time are provided.

4.1.1 All-Pathways Analysis

In an all-pathways analysis, the potential for air, groundwater (above or below the water table), surface water, and soil to carry radionuclides from E Area to off-site locations is considered. The source term analysis for a disposal facility considers how radionuclides might be directly released to these four media. The description of pathways and scenarios for the all-pathways analysis (Section 4.2.1) considers how radionuclides released to a medium may be transported within and between media to locations where human exposure may take place.

The IL disposal units are subsurface units, with overlying soil extending in excess of 2 m from the top of the units to the ground surface when closure is complete. Release to the subsurface soil surrounding the waste units by diffusion and convection is probable. Direct release of radionuclides from the disposal units to overlying surface soil, air, or nearby surface water is highly unlikely, except for release of volatile radiological components of waste (i.e., tritium, ^{14}C, and radon). Erosion of cropland near the SRS is on the order of 0.08 cm/y (from Section 3.1.4.1.6 in the CSEW report, DOE 1999b, assuming a soil matrix density of 2650 kg/m^3). However, the presence of a final vegetative cover will lower the erosion potential in a manner similar to that of a successional forest, by a factor of about 400 to 500 (Section 3.1.4.1.6 in DOE 1999b). Thus, natural processes uncovering IL Vaults during the first 1,000,000 years after disposal is not expected, but credit is only taken for the first 10,000 years. The final vegetative cover will be a climax species that prevents the growth of deep-rooted pine trees native to the area. This deterrent and the vegetative cover's capability to limit other types of biointrusion (see Section 4.2.1) makes the significant movement of nonvolatile radionuclides upwards toward the soil surface unlikely. Therefore, the source term analysis focuses on the source of radionuclides released to the groundwater in the vadose, or unsaturated, zone. With this focus, development of the source term for both the all-pathways analysis and the water-resource impacts analysis will be identical and is described in Section 4.1.3 below.

4.1.2 Air Pathways Analysis

The air pathway analysis addresses potential emission of volatile radionuclides from the E-Area LLWF, including the IL Vaults. Screening analyses (Cook and Wilhite 1998) show that only

HTO (tritiated water vapor), HT and ^{14}C could produce doses of concern via the air pathway. Therefore, I-129 releases via the air pathway need not be considered further.

4.1.3 Water Resource Impacts Analysis

The source term analysis for impacts on water resources addresses the potential release of radionuclides from the IL Vaults to the vadose zone surrounding them. Release may occur when water contacts the waste and radionuclides are leached from the waste form or when radionuclides diffuse from the units. The source term analysis requires development of a conceptual model to represent mechanisms of release and factors affecting the rate of release.

4.1.3.1 Conceptual Model of the Source Term

The rate of release for any particular radionuclide to the subsurface is a function of:

- the quantity of that radionuclide initially disposed of (i.e., radionuclide inventory)
- the rate of water infiltration into disposal units
- integrity of barriers to resist water intrusion over time
- the composition of infiltrating water contacting waste, and
- the physical form, solubility, sorptive, and diffusive behavior of the radionuclide (i.e., their physical/chemical characteristics).

Each of these parameters is discussed below, as it relates to mechanisms of release and to the conceptual model used to simulate the releases.

4.1.3.1.1 Radionuclide Inventory

Projected inventories are provided in Appendix A.

Screening I-129 for water-resource impacts analysis was not attempted, because the disposed inventory in the IL Vault exceeds the current WAC, so it is known to be a potential problem.

Screening of the large projected inventory with respect to intruder doses was not performed either (see Section 6).

4.1.3.1.2 Rate of Water Infiltration into Disposal Units

Release of radionuclides from waste is triggered by contact with water that has seeped into the waste disposal units from the surrounding vadose zone. The rate of water infiltration into the disposal units is a function of the infiltration rate of rainwater into the subsurface and the efficiency of engineered barriers that serve to divert water away from the waste in the disposal units. Boxes or other containers used to facilitate placement of waste into disposal units are not considered reliable barriers to water infiltration.

The conceptual model of water infiltration considers the types of engineered barriers (e.g., moisture barriers, vaults, grouted waste forms) associated with the disposal units (Section 3.2). Infiltration through these barriers is simulated using the numerical code PORFLOW (Appendix B), which provides estimates of rates of water movement through the subsurface soil, engineered barriers, and waste forms to the water table. More in-depth descriptions of the simulation domains used and assumptions made to estimate this transport are provided in Section 4.3.3 of the CSEW report (DOE, 1999b).

4.1.3.1.3 Integrity of Barriers to Resist Water Intrusion

Degradation of engineered barriers is expected to occur over time, thus increasing the influx of water to the wastes. Degradation will affect infiltration barriers, which are constructed for all units, and concrete vaults, containers, and cementitious or solid metal waste forms, which are present in some units.

<u>Infiltration barrier degradation</u>. Degradation of the infiltration barrier (clay/gravel drain system) is expected to occur by a number of natural processes. Potential processes include erosion, intrusion by plants and animals, and external events such as settling or slumping or a seismic

event. These processes will reduce the effectiveness of the cover in limiting the vertical moisture flux.

As presently conceived in the closure concept (Section 3.2), shallow-rooted bamboo will be planted on the disposal site and a system of drainage ditches will be constructed to handle surface runoff and diverted infiltration. During the period of active institutional control it is assumed that periodic site inspection would reveal any degradation of the overlying cover and drainage system and corrective actions would be taken. Cover degradation during the institutional control period is therefore likely to be minimal. Sheet erosion will occur, but the final vegetative cover would minimize the effects of this disturbance.

Return of the SRS land to unrestricted use at the end of the active institutional control period may result in a usage conversion to agricultural practices, consistent with past and current land use in the SRS vicinity. Row crop farming, which is consistent with historical practices in the vicinity, would increase the erosive effects of precipitation. Soil erosion rates for cropland near the SRS are on the order of 2 $kg/m^2/yr$ (Section 3.1.4.1.6). Erosion is reduced several hundred fold if a dense vegetative cover is present (Section 3.1.4.1.6). This suggests that there will be little erosion as long as the final vegetative layer has not been cleared. However, if the final vegetative layer is cleared, the cover may be eroded down to the gravel layer in as little as 650 years. Erosion of the gravel layer is difficult to predict.

In this analysis, roof failure rather than erosion was considered to be the driving factor for degradation of the infiltration barrier. The cover was assumed to remain fully functional until the roof of the vaults fails. At that time, the permeability of the gravel and clay materials are assumed to be the same as that of the top soil and backfill soil, respectively.

Vault degradation. The concrete vaults are expected to degrade slowly through a combination of physical, chemical, and mechanical processes (Walton et al. 1990). Physical and mechanical degradation processes that produce cracking are of primary concern, because of the concomitant increase in permeability. Shrinkage cracks occur as a result of the temperature cycling during curing of concrete structures, and thus are present before the facility closure cover is constructed. This allows for filling the outer portion of the cracks in the vault walls or roof with epoxy prior to closure. Cracking can occur after the vaults have been covered as a result of degradation of the epoxy used to fill shrinkage cracks, foundation settling, or rebar expansion due to corrosion. Eventually, structural failure (collapse) of the vault roofs may occur.

The principal chemical processes that disrupt the integrity of concrete structures are sulfate attack, carbonation, calcium hydroxide leaching, and rebar corrosion. The effects of these processes on vault degradation have been analyzed using a method described in Walton, et al. (1990). The analysis of chemical degradation effects and concomitant structural impacts are discussed in detail in Appendix D. The results of this analysis indicated that cracks completely penetrating the IL vault roofs are most likely to occur around 575 years for the IL vaults. Vault failure was defined as structural collapse of the vaults. This was estimated to occur at approximately 1,050 years for IL vaults. The degradation scenarios assumed for these vaults utilize these estimates for times that degradation and failure of the vaults occur. For the IL vaults, in which voids are filled in with grout, the hydraulic characteristics of the waste compartment are assumed to mimic those of native soil after roof failure.

Subsidence is an issue that must be considered for all waste disposal units at E Area. For the IL Vaults, all significant voids within the waste form are assumed to be filled with grout. Thus, only minimal subsidence is expected to occur.

4.1.3.1.4 Composition of Infiltrating Water

The composition of water infiltrating the disposal units will potentially affect the solubility or sorptive characteristics of radionuclides in the wastes. Water that has infiltrated vaults will have a composition that reflects the interaction of concrete pore water with vadose zone water. The presence of CO_2 gas in the soil and calcite present as a weathering product in the cement will buffer the pH of the water to between 7 and 8. Corrosion products of metals that are present in the disposal units, arising either from waste containers or surface contaminated wastes, may also be present in the water contacting wastes.

4.1.3.1.5 Physical/chemical characteristics.

The physical and chemical form of I-129 in high-concentration I-129 wastes disposed in the IL Vaults will vary according to the form the radionuclide is in when disposed and conditions in the disposal unit that may cause a change in form over time. Considerable uncertainty exists regarding conditions in the units over time that may cause a change of form. Therefore, assumptions regarding chemical and physical form generally are based on limited available information derived from consideration of the probable water composition in the waste disposal units, discussed above. Conservative assumptions are generally made regarding physical and chemical forms that tend to overestimate the mobility of radionuclides from the disposal units and thus overestimate the concentrations in groundwater.

However, specific sorption characteristics were assigned to high-concentration I-129 wastes based on laboratory measurements. Those measurements were made under laboratory conditions that approximated vault conditions. The measured I-129 K_ds are valid only for the specific type of waste form that was tested in the laboratory and only for I-129 concentrations at or below the concentrations for the tested materials. For materials other than the actual waste form, the K_ds for I-129 were assigned based on other site-specific tests or on literature values.

Radionuclides are assumed present as surface contamination that is leached according to laws governing solubility and sorption. Wastes are represented as porous media thus maximizing the surface area of the waste potentially exposed to infiltrating water.

Sorption coefficients (K_ds) used in the analyses of release from waste forms are listed in Table 4.1-3. Selection of K_ds was made according to the following rationale: waste-specific and site-specific values of soil K_ds are considered most appropriate; when available, they were used. Next, the comprehensive listing of default values by Sheppard and Thibault (1990) was consulted for K_ds in soil and clay. The sandy soil K_d was selected for "soil" because this value tends to be lower than for other soil types and thus is conservative (i.e., may overestimate radionuclide mobility) with respect to water-resource impacts. For concrete, a listing of K_ds by Bradbury and Sarott (1995) was consulted. For waste in which corrosion products are expected to affect sorption, K_ds were developed in Appendix E (Geochemical Interactions).

Table 4.1-3 Elemental Sorption Coefficients (K_ds) for I-129 in IL Vaults

K_d (mL/g)

Element	Soil[a]	Typical Grouted Waste[b]	Gravel[a]	Clay[c]	**Activated Carbon Vessels**[e,f]	GT-73 Resin[e]	Sludge/ Filtercake	Dowex 21K Resin[e]	Zeolite
I	0.6[d]	2	0.6[d]	1	600	3100	Unknown	1800	Unknown

[a] Values are for sand from Sheppard and Thibault (1990), unless otherwise noted.
[b] Values from Bradbury and Sarott (1995) for IL Vaults.
[c] Values are for clay from Sheppard and Thibault (1990), unless otherwise noted.
[d] Site-specific value from Hoeffner (1984).
[e] Waste-specific value from Kaplan, et al. (1999).
[f] Only waste form planned for disposal in IL Vaults.

Diffusion of radionuclides through porous media is a potentially important means of release from some E-Area waste disposal facilities, because intact engineered barriers limit convective transport. For a given porous material, it is reasonable to assume that apparent diffusion coefficients (molecular diffusion coefficients corrected for tortuosity of the porous medium) are similar for all radionuclides because molecular diffusivities in water do not vary significantly. Apparent diffusion coefficients will vary, however, between porous materials because of differences in tortuosity. Tortuosity cannot be measured directly, but apparent diffusion coefficients have been obtained empirically for conservative (nonsorbing, nonreactive, nondecaying) compounds. Apparent diffusion coefficients assumed for the various porous materials encountered are listed in Table 4.1-5. Calculation of diffusional release is part of the mass transport simulations described in Section 4.3.2 below.

Table 4.1-5 Diffusion Coefficients Assumed for Mass Transport Simulations

Material	Apparent Diffusivity (cm^2/s)	Source
Top soil and native soil	5×10^{-6}	Freeze and Cherry, 1979
Gravel	1×10^{-5}	assumed equal to molecular diffusivity without tortuosity correction
Clay	1.5×10^{-6}	Assumed to be less than value for soil, due to increased tortuosity of the more porous clay
Backfill	5×10^{-6}	assumed same as for top soil and native soil
Concrete and cementitious waste	1×10^{-8}	Liam, et al. 1992

4.1.3.2 Estimated Releases of Radionuclides

Computational analysis of the release of radionuclides from the waste to the surrounding vadose, or unsaturated, zone environment of the disposal units is an integral part of the total analysis of transport from the waste to the point of compliance for water-resource impacts analysis. This total analysis is described in detail in Section 4.3.3. A separate accounting of quantity of radionuclides released from the waste forms before transport in the vadose zone is not readily available. However, the fractional release of radionuclides to the saturated zone (i.e., fraction of original inventory released as a function of time) is readily available. Tabulated results of these calculations are provided in Section 4.3.2.

4.2 Exposure Pathways and Scenarios

The source-term analysis in Section 4.1 provides estimates of release of radionuclides from the waste disposal units to the immediate environment. These releases are considered with respect to how radionuclides might be further dispersed and ultimately lead to exposures to off-site members of the public. To evaluate exposures in terms of stated performance objectives (Section 2.5) significant pathways and scenarios relevant to estimating exposures for the all-pathways analysis and the water-resource impacts analysis must be identified. Note that the air-pathway analysis was screened out in Section 4.1.2.

4.2.1 All-Pathways Analysis

To evaluate the potential sources of off-site contamination, numerous pathways to human exposure from buried LLW are considered. A diagram of pathways to human receptors from a subsurface source of radionuclides is shown in Fig. 4.2-1. Arrows represent pathways of radionuclide movement from the source, between media (compartments represented by boxes), and eventually to a human receptor. Solid arrows represent dominant pathways, while dotted arrows represent insignificant pathways. The pathways identified in this figure are for sources undisturbed by human intrusion. Pathways pertinent to intruder exposures are addressed separately in Section 6.

4.2.1.1 Descriptions of Pathways

From the subsurface source, radionuclides can move directly into any of three media, represented by the first column of boxes in Fig. 4.2-1. Radionuclides may diffuse in the air-filled voids in the soil to the air, be moved to the surface (cover) soil by burrowing animals or deep tree roots, or be leached by infiltrating water and transported to underlying aquifers or isolated perched-water zones. The groundwater compartment represents aquifers and any isolated perched-water zones.

Volatile radionuclides from the air compartment may be transported in air and inhaled by a human receptor. These radionuclides may exchange (arrows in both directions) with the cover soil. These radionuclides may be deposited on the cover soil, and radionuclides from the cover soil may become airborne, completing the exchange process. Volatile radionuclides from the air compartment may exchange with terrestrial biota, such as crops and cattle. Volatile radionuclides may be deposited on crops or cattle, and they may become airborne again. Volatile radionuclides may be deposited on surface water and become airborne again.

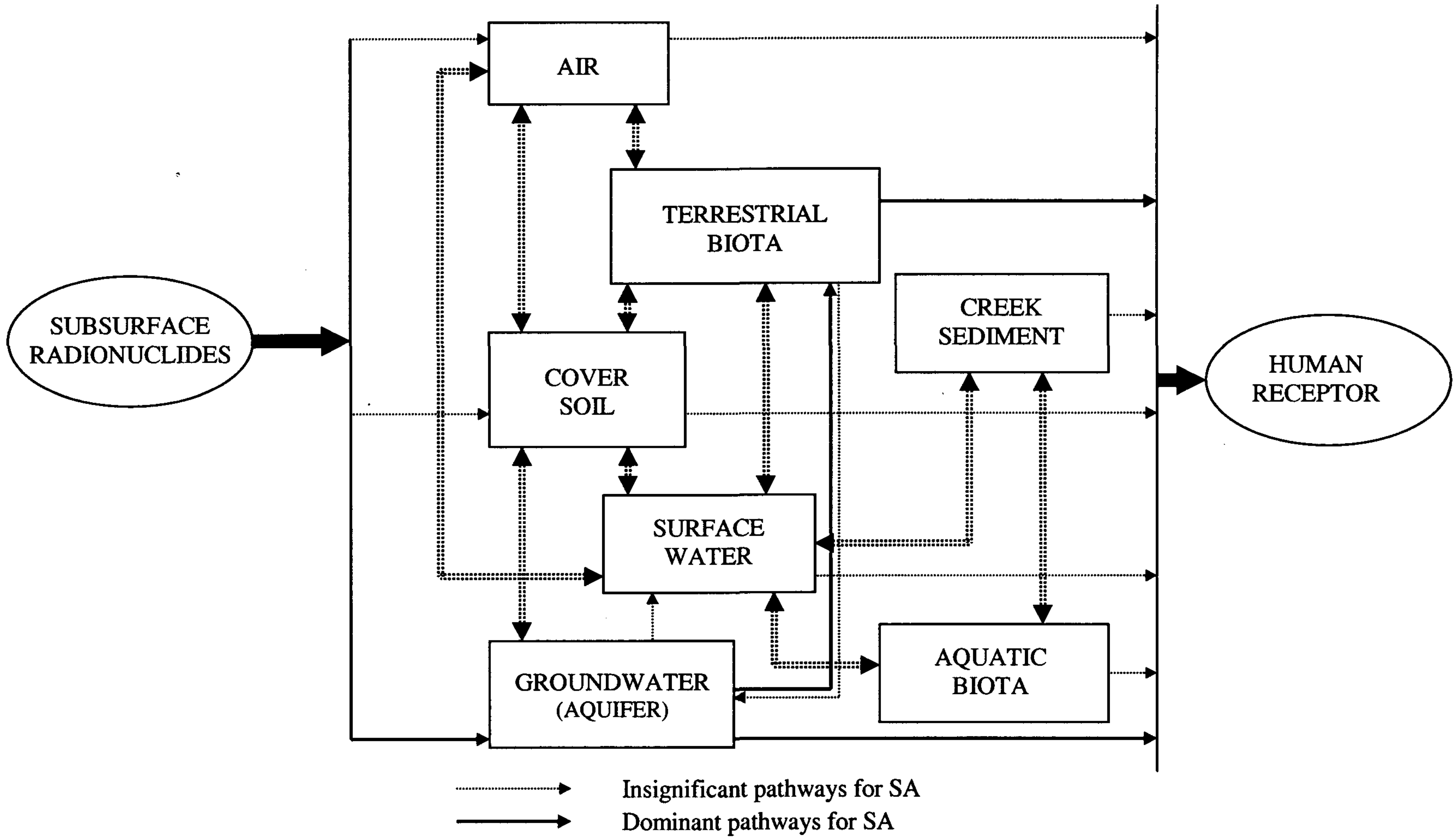

Figure 4.2-1. Pathways to Human Receptors from Subsurface Radionuclides

Cover soil radionuclides can be directly ingested by humans, such as by a child consuming dirt or by eating vegetables that are incompletely washed. These radionuclides can be exchanged with terrestrial biota. Uptake by crops and cattle can occur or they can redeposit radionuclides on the cover soil. Exchange with surface water can occur from events such as runoff and flooding. Exchange with groundwater is also possible via leaching and irrigation.

Groundwater compartment radionuclides can be directly ingested by humans. These radionuclides can be exchanged with terrestrial biota. In this particular instance, irrigation of crops can be significant (see Section 4.2.1.2), but deep roots releasing radionuclides to the groundwater is not considered to be significant. Radionuclides from the groundwater compartment may reach surface water at locations where there are seeps or streams. However, surface water does not contaminate groundwater, because the streams on the SRS are gaining streams and do not recharge groundwater.

The second column of compartments consists of Terrestrial Biota and Surface Water. Terrestrial biota radionuclides can be directly ingested by a human as crops, beef, or milk are consumed or through activities such as swimming or wading. Terrestrial biota radionuclides can exchange with surface water as cattle enter and leave streams.

Surface water radionuclides can be directly ingested by humans if surface water serves as a source of drinking water. These radionuclides can exchange with creek sediment and with aquatic biota, such as fish, because there is continual contact.

The third column of compartments consists of Creek Sediment and Aquatic Biota. The creek sediment radionuclides exchange with aquatic biota when plants or fish contact it. Creek sediments can directly affect a human wading in a stream. A human can directly ingest aquatic biota through consumption of fish, frogs, turtles, crayfish, or other aquatic creatures.

4.2.1.2 Significance of Pathways

In this section, rationale for determining the significance of pathways will be presented by working from right-to-left through Fig. 4.2-1. Special considerations for pathways are presented in the following subsection.

The third column of compartments consists of Creek Sediment and Aquatic Biota. Exposure from consuming contaminated fish, frogs, turtles, crayfish and similar aquatic creatures in the aquatic biota compartment is not considered to be significant health risk, because dilution is considerable in the nearby creeks. Groundwater radionuclide concentrations near the disposal units are expected to exceed surface water concentrations by orders of magnitude. Thus, ingestion of aquatic biota is expected to result in lower exposures than from direct ingestion of groundwater. A possible exception is C-14 in fish as shown in the Composite Analysis (WSRC 1997b), but C-14 is not applicable for the I-129 analysis in this report.

There is only slight opportunity for a human to be exposed to creek sediment compartment radionuclides. Concentrations in creek sediments likely will be much lower than concentrations in groundwater, causing radionuclides traveling along pathways through this compartment to be insignificant in terms of possible exposures.

The second column of compartments consists of Terrestrial Biota and Surface Water. There is a significant exposure risk from consumption of contaminated crops, beef, or milk in the terrestrial biota compartment. Groundwater is the primary compartment feeding the terrestrial biota compartment, hence arrows connecting the subsurface radionuclides, the groundwater compartment, the terrestrial biota compartment and the human receptor are all solid, thick lines. Little I-129 can reach the cover soil, except through irrigation. However, irrigation of cover soil by groundwater is practiced only occasionally in the SRS region, due to normally abundant precipitation during the growing season (Murphy 1990). Hence, although this pathway poses a significant risk, the risk is reduced by the limited irrigation.

There is only a slight exposure risk from surface water radionuclides, because concentrations are much lower than they are for the groundwater. Exchanges with terrestrial biota are much less significant than those from irrigation, because that exchange is primarily with deep-rooted trees that are not ingested by human receptors.

The first column of compartments consists of Air, Cover Soil and Groundwater (Aquifer). I-129 is not a highly volatile radionuclide so the air pathway is insignificant. There is only a slight exposure risk from cover soil radionuclides, because direct human ingestion is minimal. Direct ingestion by a human of the groundwater radionuclides is significant, due to high concentrations. The arrows from the subsurface radionuclides to the groundwater compartment and to the human receptor thus are solid, thick lines.

Based on the discussion above, only two sets of transport pathways are considered to be of significant consequence to off-site members of the public and are considered further in this SA. These pathways, indicated by solid arrows in Fig. 4.2-1, include:

1) leaching of the waste form resulting in contamination of groundwater local to E Area and direct ingestion of that groundwater

2) leaching of the waste form resulting in contamination of groundwater local to E Area, irrigation of livestock and crops, and ingestion of meat and milk from livestock that drink the contaminated irrigation water or ingestion of crops irrigated with that groundwater

4.2.1.3 Special Considerations for Pathways

Both pathways of concern in the all-pathways analysis include groundwater. A special consideration for the groundwater pathway is contaminant movement as colloids. Radionuclides may move through groundwater either as dissolved constituents or in a suspended colloidal form. Colloidal migration is a very dynamic process. As suspended colloids encounter slight changes in water chemistry or flow rate along a flow path, they may either deposit on the immobile soil surfaces or become mobilized. Therefore, colloidal transport in natural aquifer media can be viewed as a process with attributes similar to those governing sorption and desorption of elements and compounds. Colloidal forms are not explicitly addressed in this analysis for two reasons, discussed below.

First, colloidal forms are not directly addressed in this analysis because reliable means of predicting site-specific colloidal influences on solute migration are not available. The types of colloids present are not readily measured, and thus the sorptive potential and stability of the colloids cannot be projected. Second, colloids migrate according to complex physical and chemical immobilization and remobilization mechanisms. These mechanisms are not easily determined in non-idealized media such as natural aquifer materials. Because of these and other uncertainties, conservative assumptions are used in the SA to assure that these indeterminate effects attributable to colloids will not have a significant influence on the results.

For liquid transport computations used in this analysis, a sorption coefficient, normally referred to as a K_d, is used to represent the partitioning of a radionuclide between the solid and liquid phases. Coefficients for each radionuclide are empirically determined and are calculated from experimental tests that either measure "liquid phase" and solid phase concentrations of radionuclides or measure the retardation that occurs as a result of reversible sorption processes when liquid constituents move through a porous medium. "Liquid phase" in both of these measurements is defined as that portion of the experimental media that passes through a filter of a specified pore size. Because of this definition, the "liquid phase" may actually contain colloids that pass through the filter. This colloidal material is very sorptive because the particles are small with a very high surface-to-volume ratio. Thus, the colloidal fraction passing through the filter with the liquid tends to artificially increase the "liquid phase" concentration, which decreases the K_d of the porous media being tested. Because an experimental K_d may be too low, calculated doses from liquid pathways will be conservative.

4.2.1.4 Receptor Locations

The nearest location from the disposal site for off-site members of the public depends on the time after disposal. During the period of active institutional control, i.e., for the first 100 years after facility closure, off-site members of the public are assumed to be located no closer to the disposal site than the present boundary of the SRS. After active institutional control ceases, off-site members of the public could be located as close as 100 m from any of the E-Area disposal units (the buffer stated in DOE Order 435.1, DOE 1999a).

Doses to the off-site public from contaminated groundwater exposure pathways at 100-m distances from the disposal units are not considered during active institutional control due to the following reasons:

1) the design and closure concepts for the disposal units that are intended to inhibit infiltration of precipitation, and

2) the considerable distance from the disposal site to the present boundary of the SRS.

Thus, during the period of active institutional control, the closest member of the public is considered to be at the SRS site boundary. Doses during the active institutional control period are ignored, because the doses at the site boundary should be much lower than later doses from 100-m well water. During the active institutional control period contaminated groundwater will discharge to surface streams within the SRS and considerable dilution will be provided by the streams.

In summary, for dose analyses an off-site member of the public is assumed to use water from a well for domestic purposes. That well is assumed to be at least 100 m from the vaults where the maximum concentrations of radionuclides in groundwater are projected to occur after loss of active institutional control.

4.2.2 Water Resource Impacts Analysis

The information in this section is identical to that in the same titled section of the CSEW report (DOE 1999b), except that this report is limited to I-129.

The I-129 values for Table 4.2-3 are reproduced below. The Maximum Contaminant Levels (MCLs) for the three options of specifying the performance measure for groundwater impacts analysis are given in Table 4.2-3. All MCLs are given in units of pCi/L to facilitate comparisons of the different options, even though the primary standard for beta/gamma-emitting radionuclides in all options is a dose limit rather than a limit on concentration.

Table 4.2-3 Maximum Contaminant Levels for Radionuclides in Groundwater Corresponding to Different Options of Groundwater Impacts Requirements[a]

Radionuclide	Option 1[b]	Option 2[b]	Option 3[b,c]
^{129}I	0.5	0.6	21

[a] Different options are described in Section 2.5.2 of DOE, 1999b and Section 4.2.2.
[b] Values are in units of pCi/L, unless otherwise noted.
[c] Value calculated by EPA (1991), unless otherwise noted.

To compare the dose from the drinking water pathway relative to the dose from the milk and meat pathways, ^{129}I was examined using an F_m of 0.01 and an F_f of 7.0E-3 (Baes, et. al 1984). The drinking water pathway dose is more than 7 times greater than the dose from the milk and meat pathways.

4.3 Analysis Method

The conceptual models developed for analyzing potential transport for radionuclides from the IL Vault disposal units of E Area to the points of compliance associated with the performance objectives are described in this section. Methods used to implement these models, assumptions made in implementation, and justification for the assumptions are also discussed.

4.3.1 All-Pathways Analysis

Based on the discussion in Section 4.2.2 the only I-129 exposure pathway of concern for the all-pathways analysis is the pathway that involves direct ingestion of groundwater. In large part, the analysis of this pathway is identical to that for the water-resource impacts analysis, and thus is described in Section 4.3.2. Doses to the off-site members of the public from ingesting contaminated groundwater beyond the 100-m buffer zone around all disposal units were not directly estimated. Rather, comparisons of maximum projected groundwater concentrations with the more restrictive of either MCLs (Table 4.2-3) or allowable concentrations based on the 25-mrem per year performance objective were made. The allowable concentrations were calculated by dividing the 25 mrem per year value by the EDE per unit concentration in drinking water (Table C.3-5, Appendix C.3). A composite listing of MCLs and allowable concentrations based on the 25 mrem/yr limit is given in Table 4.3-1.

Table 4.3-1 Comparison of MCLs and Allowable Groundwater Concentrations Based on the 25 mrem Per Year Performance Objective for Off-Site Individuals

Radionuclide	MCL,[a] pCi/L	Allowable Concentration Based on 25 mrem per Year, pCi/L[b]
^{129}I	0.5	130

[a] Option 1, Table 4.2-3, unless otherwise noted.
[b] Calculated from Table C.3-5

4.3.2 Water-Resource Impacts Analysis

The analysis for water-resource impacts requires that transport of radionuclides from the waste disposal units to the compliance points for groundwater impacts (Section 2.5.2 in DOE, 1999b) be simulated. To conduct these simulations, conceptual models were developed representing the disposal units and surrounding vadose zone to facilitate computation of radionuclide transport to the aquifer. A conceptual model for transport in the saturated zone was also developed. The conceptual models define how features of the disposal units and the subsurface environment are represented in the numerical models used to conduct the transport simulations. The key assumptions and values of parameters assumed for this analysis are described below.

Conceptual models of radionuclide transport are of two main types: models describing vadose, or unsaturated, zone transport (which include transport through disposal unit barriers); and a model describing transport through the saturated zone beneath the water table to the point of compliance. The vadose zone model is unique to the disposal unit's design characteristics that influence the flow of water and transport of radionuclides through the materials present. The saturated zone model represents the aquifer units underneath all E-Area disposal units; therefore, only one saturated zone conceptual model is needed for the entire facility.

Results of the saturated zone model simulations are reported in terms of the maximum groundwater concentration at the compliance point per Ci of each radionuclide disposed in an IL Vault. This fractional concentration is compared to the MCL or to the allowable concentration based on the 25-mrem all-pathways performance objective, when the latter is more restrictive than MCL (see Section 4.2.2). This comparison (dividing the MCL by the fractional concentration) yields an inventory limit for each radionuclide, which is reported in Section 5.

4.3.2.1 Vadose Zone Model of IL Vaults

Release of radionuclides from the IL vaults to the vadose zone will occur when water enters the vaults, contacts the waste, dissolves or desorbs radionuclides, and subsequently exits the vaults (Section 4.1.3). Diffusion may also occur. Factors affecting this release are the rates of water movement through the vaults and waste and the solubility, sorption, and decay characteristics of the radionuclides. Once in the surrounding vadose zone, transport of radionuclides will be influenced by the same factors, but for different materials through which the radionuclides travel.

The conceptual model of the IL vaults considers movement of water and radionuclides through the vadose zone and waste disposal units in 2-dimensions. The 2-dimensional model represents the right half of a transverse section through an IL vault and the surrounding porous media, as shown in Fig. 4.3-1. Analysis in 2-dimensions is sufficient for this problem, because releases along the length of the vaults are expected to be uniform except at each end of a vault. Releases from the end-planes of the vaults are expected to be insignificant relative to releases from the combined areas represented by the bottoms and sides of the vaults, and thus no corrections are made to account for these releases. The results in 2-dimensions, which assume a unit width in the third dimension, are readily adapted to 3-dimensions.

The upper part of the domain of the IL vault conceptual model is the ground surface (Fig 4.3-1). The lower part of the domain is the water table. Directly beneath the ground surface is top soil, underlain by the sloped (2% grade) gravel and clay layers of the infiltration barrier. Water prohibited from infiltrating by the clay layer is assumed to flow to a conceptual drain, representing any means of diverting water from the vaults. It is assumed that drainage around individual vaults is sufficient to carry excluded water away from the vaults during the time that the infiltration barrier is intact (100 years). Underneath the infiltration barrier is the backfill used to fill under, to the sides, and over the constructed and filled vaults. Finally, the concrete roof,

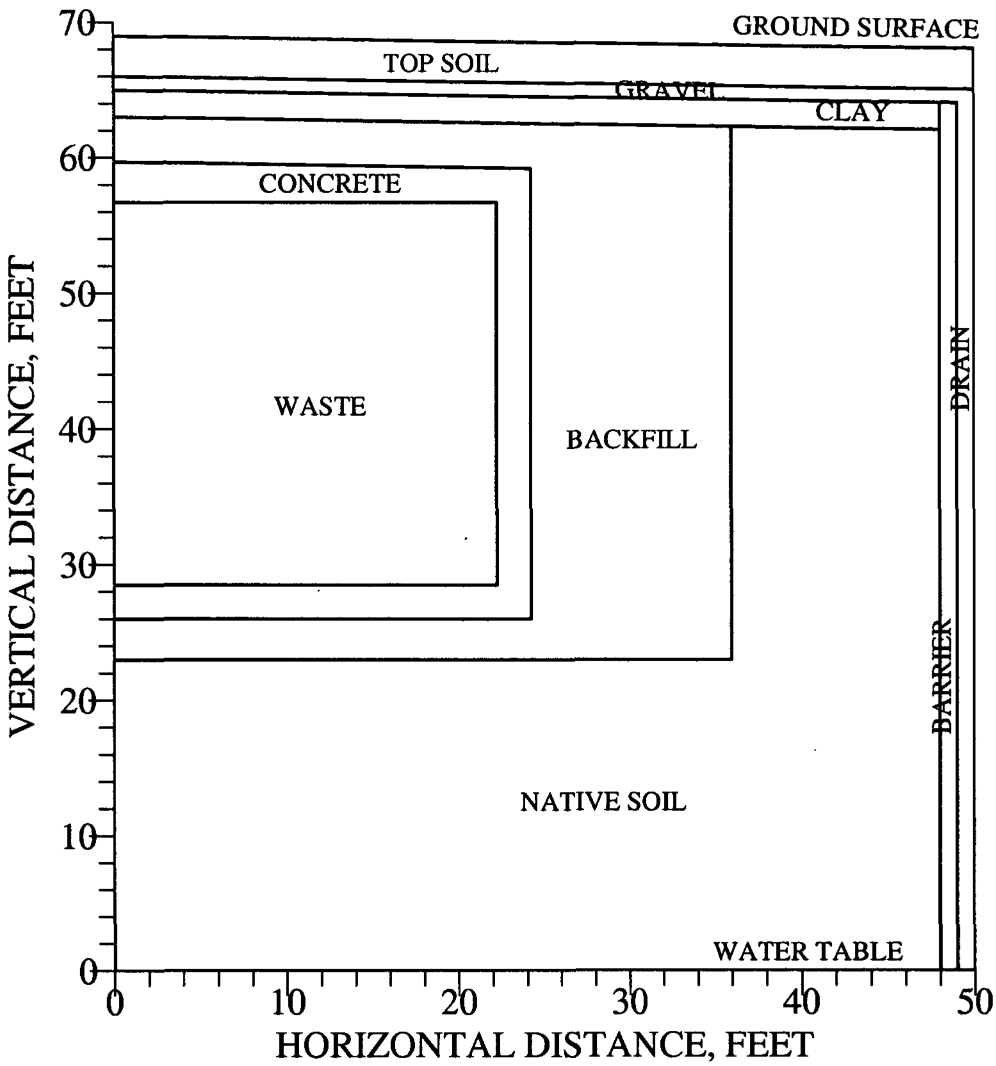

Figure 4.3-1. Conceptual model of IL vault

walls, and floor of the vaults are represented, as well as the waste placed in the vaults. The base of the vaults is represented at approximately 7.6 m (25 feet) above the water table. The IL waste is to be grouted in place or enclosed in concrete. However, the grout is only assumed to maintain a high pH level which actually reduces the K_d for I-129 (Kaplan, 1999). The entire waste volume was assumed to consist only of the waste form. Although voids will exist for tritium crucibles and some other waste forms, release from the vaults during the intact phase will be controlled by high Kd waste. A discretization of the IL vault domain is shown in Fig. 4.3-2.

The barrier at the right side of the IL vault domain, adjacent to the drain, represents a location far enough from the vaults that flow is expected to be vertical and unaffected by the flow of water diverted around the low permeability vaults. No lateral flow is expected at this location and an imaginary barrier was added so that water from the conceptual drain does not reenter the interior of the domain at this point. The left side of the IL vault domain is a line of symmetry midway through the transverse section of the IL vault. Symmetry forces flow at this point to be vertical.

The conceptual model for the IL vault depicted in Fig. 4.3-1 defines the vertical and lateral extent of the simulation domain used to perform flow and mass transport computations. The domain discretization (Fig. 4.3-2) includes about 2700 small elements (a 43×63 grid) for which the flow and transport equations are solved numerically. The PORFLOW code (Appendix B) was used for flow and transport simulations.

To solve the flow equations, boundary conditions and hydraulic properties of the materials present in the simulation domain were specified. The top of the domain is a constant flux boundary, where net infiltration (rainfall less evapotranspiration and other losses) is applied. An infiltration rate of 40 cm/yr is assumed (Appendix C). The bottom of the domain is a constant head boundary, maintained by the presence of the water table. The left and right boundaries are no flow boundaries, where flow is essentially vertical and parallel to these boundaries, as described above.

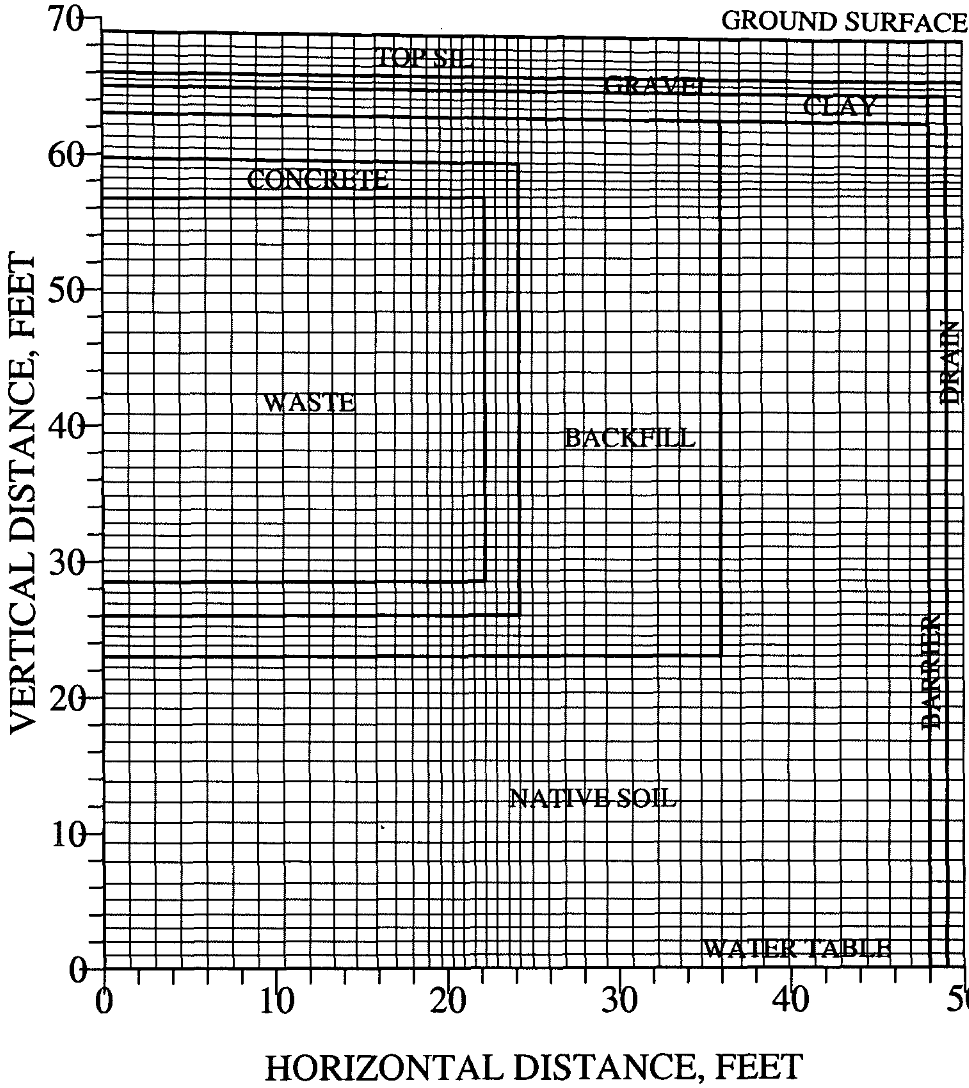

Figure 4.3-2. Modeling grid of IL vault

Hydraulic properties of the materials present in the simulation domain were assigned according to a complex rationale described in Appendix C. Assignment of these properties requires spatial averaging, such that each of these materials is treated as if they are homogeneous and isotropic porous media. These properties change with time, according to the degree of degradation assumed to have occurred in the vaults. For the IL vaults, three different conditions occur over time (Table 4.1.2, Section 4.1.3):

- the intact condition, occurring from the time of closure to 575 years post-closure
- the degraded condition, occurring between 575 and 1050 years post-closure
- the failed condition, occurring after roof failure, which is estimated to occur at 1050 years post-closure (Appendix D).

Table C.1-1 lists the hydraulic conductivity, porosity, and type of moisture characteristic curve assumed for each material under these three conditions.

Steady-state simulations of flow were conducted for the three conditions defined for the IL vaults. These simulations used hydraulic properties listed in Table C.1-1.

Mass transport simulations were run using the steady-state flow fields generated for all three scenarios, and were based on an initial activity of 1 Ci of I-129 present in one IL vault. Simulations were conducted for each type of I-129 waste using its measured K_d. Boundary conditions for mass transport were assumed as follows: at the top and bottom of the domain, a concentration of zero was assigned, which corresponds to the assumption that contaminants reaching either boundary are rapidly swept away from the vicinity of contact. This assumption serves to maximize the simulated diffusive flux through the domain, which is driven by concentration gradients, and thus, is conservative. At the left side of the domain, a no-flux boundary was assigned because of symmetry with the left half of the vault. At the right side of the domain, a no-flux boundary was assigned because of the drain.

K_d's listed in Table 4.1-3 were used for each I-129 waste form. Apparent diffusion coefficients from Table 4.1-5 were assumed. Longitudinal and transverse dispersivities were assumed to be zero cm. This assumption may delay simulated arrival of the leading edge of a plume at the water table slightly, but it is conservative because the plume is more concentrated by neglecting dispersion. Estimated fluxes at the water table are reported as Ci/yr per Ci initially in the disposal unit. These reporting units facilitate calculation of inventory limits, and are readily scaled to the initial inventory of each radionuclide listed in Appendix A.

Peak fractional fluxes to the water table for I-129 waste forms simulated are given in Table 4.3-4. Hypothetical waste forms with K_ds that were expected to cover the K_d range for actual waste were also modeled and their peaks are shown in Table 4.3-4. The peak fluxes for all waste forms occur soon after roof failure, which is estimated to occur at 1050 years.

Table 4.3-4. Estimated peak fractional flux to the water table for I-129 waste forms

I-129 Waste Form	K_d	Peak fractional flux to water table	Time of peak flux	Peak Normalized Concentration at 100-m Well	Time of peak flux
	ml/g	Ci/yr per Ci inventory	Yr	PCi/L per Ci inventory	Yr
Hypothetical	2	1.63E-2	1100	975.5	1120
Hypothetical	20	1.71E-3	1120	104.8	1140
Hypothetical	200	1.71E-4	1120	10.52	1140
Activated Carbon[a]	600	5.70E-5	1120	3.506	1140
Hypothetical	1000	3.42E-5	1120	2.104	1140
Dowex 21K Resin	1800	1.90E-5	1120	1.169	1140
Hypothetical	2000	1.71E-5	1120	1.052	1140
GT-73	3100	1.10E-5	1120	0.6786	1140

[a] Waste form planned for disposal in IL Vaults

This peaking behavior occurs primarily because of the jump in infiltration when the roof fails. This jump in water speed is accompanied by an increase in the volume of water present in the vadose zone as the saturation increases. The increased water volume translates into more contamination in the water, because of partitioning. For all cases, once contamination is released from the waste it moves rather quickly through the underlying materials because of their low K_d values. The concrete has a low K_d of 2 ml/g and the underlying vadose zone materials have an even lower K of 0.6 ml/g. Movement through the aquifer is quick because of the high aquifer water speed and its low K_d.

4.3.2.2 Saturated Zone Model of E Area

4.3.2.2.1 Model Types

To calculate peak groundwater concentrations at the points of compliance for the all-pathways analysis and water-resource impacts analysis, transport in the saturated zone of radionuclides leached from the waste disposal units and reaching the water table must be evaluated. There are two main components to this evaluation: 1) development and simulation of a saturated flow model; and 2) development and simulation of a contaminant transport model for the saturated zone.

4.3.2.2.2 Numerical Flow Model

The numerical flow model for the IL Vaults is identical to that for cement-stabilized encapsulated waste trenches at the E-Area LLWF. Thus, Section 4.3.3.2.2 in DOE, 1999b provides the needed description of the numerical flow model for this SA.

4.3.2.2.3 Numerical Transport Model

The numerical transport model for the IL Vaults is identical to that for cement-stabilized encapsulated waste trenches at the E-Area LLWF. Thus, Section 4.3.3.2.3 in DOE, 1999b provides the needed description of the numerical transport model for this SA. The only difference is that the source term is produced in the IL Vault, rather than in trenches.

Locations of the IL Vaults were interpreted in terms of this simulation grid. Two vaults were represented on this grid as shown in Figure 4.3-5. Results of the transport simulations are provided in tables in Section 5 and shown graphically in Appendix G.

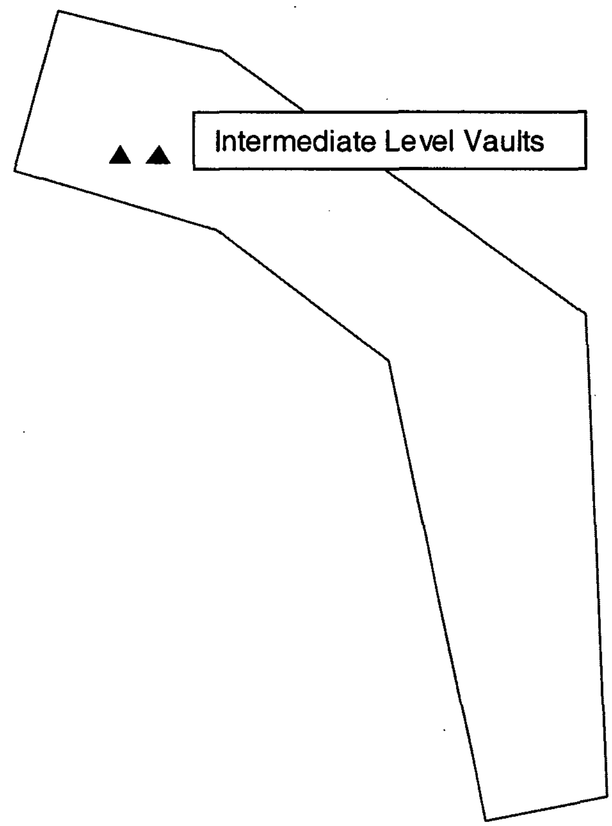

Figure 4.3-5. Location of the IL Vaults

SECTION 5

RESULTS OF NON-INTRUDER ANALYSES

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5. RESULTS OF NON-INTRUDER ANALYSES

In this section, the results of the analysis of performance of the IL Vaults in the E-Area LLWF are presented for non-intruder scenarios. As described in Section 4.2, the analyses focus on ingestion of radionuclides in groundwater for the all-pathways and water-resource impacts analysis. In Section 5.1, projected groundwater concentrations and calculated inventory limits used in evaluating performance objectives for protection of the public and performance requirements to assess water-resource impacts (Section 2.5) are presented. In Section 5.2, the results of sensitivity and uncertainty analyses are discussed, to gain perspective on the meaning of the results in Section 5.1. Finally, in Section 5.3, application of the As Low As Reasonably Achievable (ALARA) process to the design and operation of the IL Vaults in the E-Area LLWF is discussed.

5.1 Results of All-Pathways Analysis and Water-Resource Impacts Analysis

Section 4.2 established that the only significant pathway of concern for the all-pathways analysis is groundwater ingestion, with the endpoint of the analysis being evaluation of dose. The endpoint of the water-resource impacts analysis is estimated groundwater concentrations at the same compliance point as that used in evaluating protection of the public: the point of highest concentration outside a 100-m buffer zone around disposal units. The performance objective of 25 mrem/yr for protection of the public in the all-pathways analysis can readily be converted to an allowable groundwater concentration limit. The 25 mrem/yr limit is divided by the EDE of any given radionuclide per unit concentration in groundwater (Table 5.1-1). Therefore, endpoints of performance measures for protection of the public and analysis of water-resource impacts can both be expressed in terms of groundwater concentration in this SA. The following discussion addresses results of the all-pathways analysis and water-resource impacts analysis together, because the same calculated groundwater concentrations can be used to evaluate each performance measure.

Table 5.1-1 Annual EDEs from Drinking Water Pathway Per Unit Concentration of Radionuclides in Water

Radionuclide	EDE rem/yr per µCi/L
^{129}I	2.0E+02

The methods for calculating groundwater concentrations at the compliance point for protection of the public and for water-resource impacts analysis were described in Section 4.3. Briefly, groundwater concentrations at the compliance point were calculated by using the vadose zone models (simulated with PORFLOW) to calculate contaminant flux to the water table as a function of time. Fractional fluxes (Ci/yr per Ci disposed) were estimated and used as the source term to the saturated zone model. Groundwater concentrations (pCi/L per Ci disposed) were then calculated using PORFLOW. Results of the PORFLOW analyses are shown graphically in Appendix G.

The groundwater concentrations presented in this section are in normalized units (pCi/L per Ci) to facilitate computation of inventory limits for IL Vaults. Ultimately, the more restrictive of either the MCLs (in pCi/L) or allowable concentrations (in pCi/L) based on the 25 mrem/yr performance objective can be divided by the normalized groundwater concentrations to derive an inventory limit. Calculated inventory limits, based on the peak groundwater concentrations, are also presented in this section.

Table 5.1-2 provides the maximum projected groundwater concentrations of radionuclides at the compliance point for protection of the public and for water-resource impacts analysis, normalized to a one-Ci source of each waste form listed in the inventory (Appendix A). In Table 5.1-3, calculated inventory limits based on the peak groundwater concentrations up to 10,000 years are given. Inventory limits for two vaults are calculated by dividing the concentration limit by the peak groundwater concentration. Because flux results from the vadose zone model were split between two cells in the aquifer model (representing locations below two IL Vaults), the inventory limits for one vault is calculated by halving the limit for two vaults.

Table 5.1-2 Peak Groundwater Concentrations for the High-Concentration I-129 Waste Simulations

Waste Form	Kd ml/g	Peak up to 10,000 years [a] pCi/L per Ci	Time of peak yr
Hypothetical	2	975.5	1120
Hypothetical	20	104.8	1140
Hypothetical	200	10.52	1140
Activated Carbon[b]	600	3.506	1140
Hypothetical	1000	2.104	1140
Dowex 21K	1800	1.169	1140
Hypothetical	2000	1.052	1140
GT-73	3100	0.6786	1140

[a] Estimated with PORFLOW
[b] Waste form planned for disposal in IL Vaults

Table 5.1-3 Calculated I-129 Inventory Limits for One IL Vault Based on the Groundwater Pathway

Waste Form	K_d ml/g	Concentration limit[a] pCi/L	Peak groundwater concentration up to 10,000 years[b] pCi/L per Ci	Calculated inventory limit[c] Ci/vault
Hypothetical	2	.5	975.5	2.56E-4
Hypothetical	20	.5	104.8	2.39E-3
Hypothetical	200	.5	10.52	2.38E-2
Activated Carbon[d]	600	.5	3.506	7.14E-2
Hypothetical	1000	.5	2.104	1.19E-1
Dowex 21K	1800	.5	1.169	2.08E-1
Hypothetical	2000	.5	1.052	2.27E-1
GT-73	3100	.5	0.6786	3.57E-1

[a] The more restrictive of either the MCL or the allowable concentration based on a 25 mrem/yr performance objective (Table 4.3-1)
[b] Peak concentration is per Ci disposed of in two IL Vaults.
[c] Calculated by dividing the "Concentration limit" by the "Peak groundwater concentration" and dividing by 2 to normalize to one IL Vault.
[d] Waste form planned for disposal in IL Vaults

The inventory limits form an essentially linear relationship with the K_d. The data points from Table 5.1-3 are plotted in Figure 5.1-1. The best-fit linear equation is as follows:

$$\text{Inventory Limit (Ci/vault)} = 1.188\text{E-}4 * K_d \text{ (ml/g)} + 1.504\text{E-}6.$$

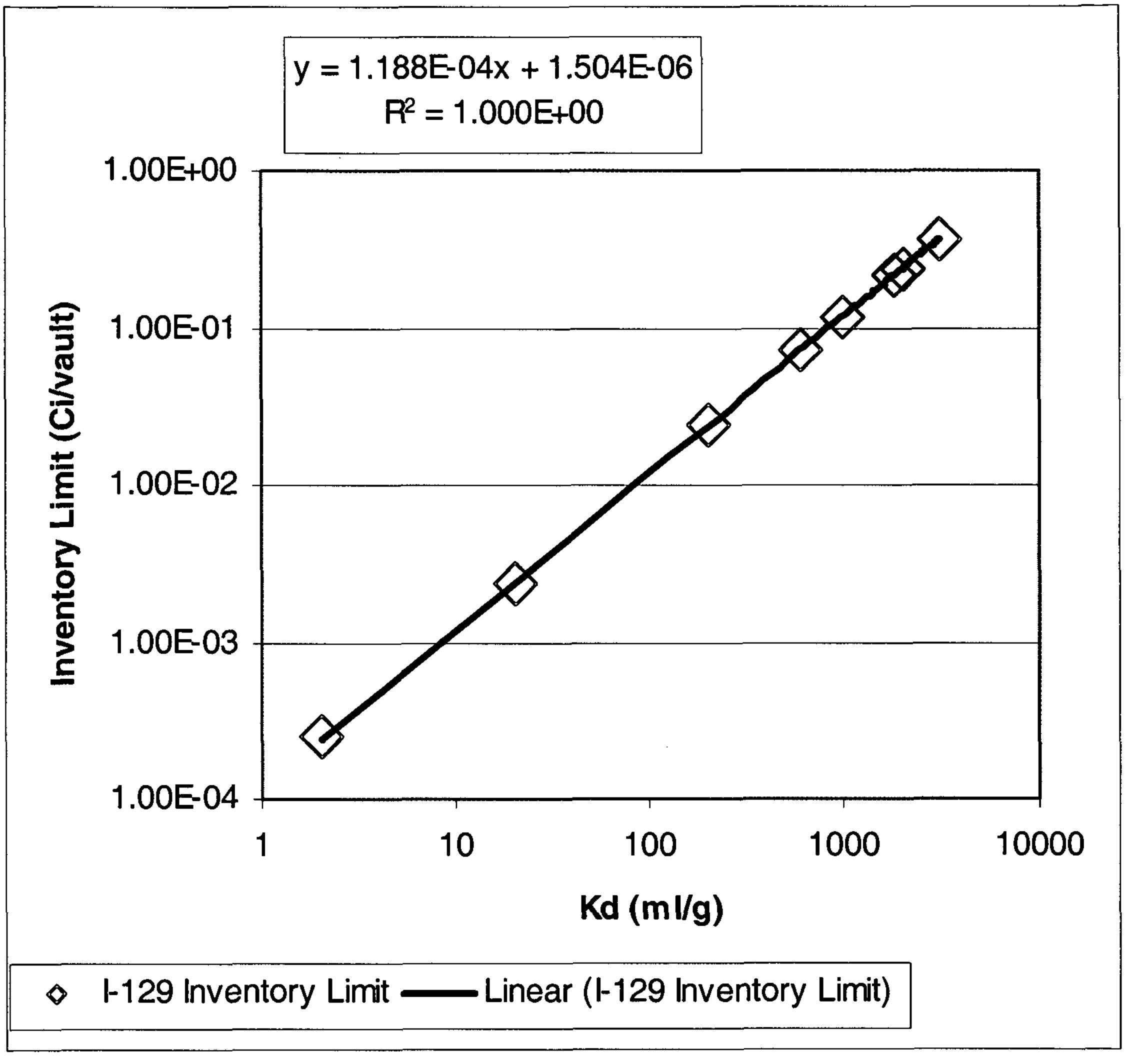

Figure 5.1-1. Inventory Limits as a Function of Kd

The data are more nearly linear at the higher K_d values. This equation can be used to estimate the inventory limits for high-concentration I-129 wastes with measured K_d values.

5.2 Results of the Sensitivity and Uncertainty Analysis

The sensitivity and uncertainty analysis is discussed in the similarly titled section in the CSEW report (DOE, 1999).

5.3 ALARA Analysis

The ALARA analysis is discussed in the similarly titled section in the CSEW report (DOE, 1999).

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SECTION 6

INADVERTENT INTRUDER ANALYSIS

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6. INADVERTENT INTRUDER ANALYSIS

Section 6 is identical to Section 6 from the CSEW SA until Section 6.3.1, where the dose analyses commence, with minor distinctions. The distinctions are as follows:

- the target is the IL Vault rather than a CSEW trench
- the volume of a single disposal unit is 5,700 m^3 rather than 5,760 m^3
- the geometrical reduction factor (G) is 0.4 rather than 0.6, and
- the only radionuclide of interest is I-129.

6.3.1 General Dose Analysis for Agriculture Scenario

Application of the models in Equations 6.3-1 through 6.3-5 to the IL Vaults produced the results of the dose analysis for the intruder-agriculture scenario.

6.3.1.1 Analysis of Intermediate-Level Vaults

Because of the design of the IL vaults, the agriculture scenario involving direct excavation into the waste is not expected to become credible until long after disposal. Because the waste will be located well below the ground surface, a considerable amount of erosion will need to occur before the waste could be accessed by normal excavation procedures for a home. Then, the concrete roof and layer of uncontaminated grout above the waste are expected to preclude excavation into the waste for as long as they maintain their physical integrity. The assumed performance of the three barriers to excavation into waste is discussed below.

The current closure concept for the IL vaults calls for an earthen cover above the concrete roof of thickness about 3 m (Sect. 3.2). From data provided in Sect. 3.1.4.1, the average erosion rate for cropland near the SRS is about 2 kg/m^2 - yr, or 1.4 mm/yr assuming a reasonable average bulk density of cover soils of 1400 kg/m^3. This erosion rate probably is an upper-bound estimate for the earthen cover, because an estimated erosion rate for natural successional forests (see Sect. 3.1.4.1) is about 0.003 mm/yr. Excavation for a home normally is assumed to extend no more than about 3 m below the ground surface (NRC 1981; Oztunali and Roles 1986). The total thickness of the concrete roof and layer of uncontaminated grout above the waste in the IL vaults is expected to be about 1.7 m (see Sect. 3.2); therefore, at least 2.7 m of the earthen cover would need to erode before a significant thickness of the waste (about 1 m) would be accessible during excavation, such that significant exposures according to the agriculture scenario could occur. Using the estimated erosion rates given above, the time required for 2.7 m of cover material to erode is estimated to be about 2,000 years and perhaps as long as 900,000 years. The very low erosion rate for natural successional forests is difficult to justify for such a long time. However, a gravel layer about 0.9 m below the surface in the current closure concept undoubtedly would inhibit further erosion once the gravel layer is exposed. Therefore, erosion to a depth necessary to permit normal excavation into the waste presumably will not occur for at least several thousand years after disposal.

The models for degradation of the concrete roof are described in Section 4.1.3.1 and Appendix D. As indicated in Table 4.1-2, the roof above an IL vault is expected to maintain its integrity for about 1,000 years after disposal, and collapse of the roof is expected to occur at about that time. If the roof were in the form of rubble after collapse, which probably represents a worst-case scenario, excavation through the collapsed roof could occur at that time.

After the concrete roof over an IL vault fails, the layer of uncontaminated grout above the waste presumably must weather almost entirely to soil-equivalent material before excavation into the waste would become credible. To estimate the weathering rate of grout, this material is assumed to resemble carbonate rock (e.g., limestone) in its weathering properties. Available data summarized by Ketelle and Huff (1984) indicate that the weathering rate of carbonate rock in regions near the SRS is in the range 35 to 100 mm per 1,000 years. For purposes of this analysis, a weathering rate for the layer of uncontaminated grout of 100 mm (0.1 m) per 1,000 years is assumed. This value applies to the expected infiltration rate of water in native soil of 40 cm/yr (see Appendix C.1.1) and, thus, applies at times after the concrete roof has failed at about 1,000 years after disposal. A weathering rate at the upper end of the range of reported values for carbonate rock is chosen, because grout should have a somewhat higher porosity than average carbonate rock and correspondingly be more susceptible to weathering by infiltrating water.

The nominal thickness of the uncontaminated grout layer above the waste in the IL vaults is 3 ft (90 cm). Dividing the thickness of the grout by the weathering rate of 100 mm per 1,000 years leads to an estimate of 9,000 years. This estimate is based on the assumption that essentially all the grout layer must weather to soil-equivalent material before excavation into waste becomes credible. This estimate shows that even in the absence of a concrete roof, the layer of uncontaminated grout above the waste should prevent excavation into the waste for many thousands of years after disposal.

The analysis described above assumes that excavation into the waste could occur as soon as the concrete roof has failed and the layer of uncontaminated grout above the waste has weathered to soil-equivalent material. This assumption probably is conservative because the space between waste packages in the IL vaults will be backfilled with grout, and the top layer (about 1 m) of this grout presumably must weather to soil-equivalent material before significant excavation into the waste could occur. The weathering rate of this material presumably would be about the same as for the grout layer above the waste described above. Therefore, about 10,000 years presumably would be required for a 1-m thick layer of grouted waste to weather to soil-equivalent material. This time is in addition to the time required for weathering of the grout above the waste.

In summary, the concrete roof above the vaults, the layer of uncontaminated grout above the waste, and the grouting of the waste are expected to be effective barriers to excavation into the waste for many thousands of years after disposal. An analysis of the expected performance of the earthen cover above the IL vaults, the concrete roof and the grout layers in the vaults indicates that excavation into the waste probably is not credible for at least 20,000 years after disposal. The gravel layer in the earthen cover, which will be placed about 3.5 m above the waste, presumably will be quite erosion-resistant, and a typical excavation to a depth of about 3 m below the gravel surface would not access waste. Even if the gravel layer were subject to the same erosion rate as native soil, the time required for a sufficient thickness of the cover to erode so that about 1 m of waste would be accessible by excavation should be at least several thousand years and could approach one million years if the current erosion rate for natural successional forests at the SRS is sustained.

From the analysis of the earthen cover and engineered barriers for the IL vaults presented above, it is clear that the intruder-agriculture scenario is not credible for well beyond 1,000 years. Furthermore, only long-lived radionuclides in the waste possibly could be of concern in an analysis of the agriculture scenario for inadvertent intruders. In this analysis, results are presented for 20,000 years after disposal, which is the earliest time that the engineered barriers are expected to have failed sufficiently to permit excavation into a layer of waste about 1-m thick.

The results of the dose analysis for the agriculture scenario are given in Table 6.3-5. The results were calculated using Equations 6.3-4 and 6.3-5. The scenario dose conversion factors (SDCFs) for the long-lived radionuclides of concern are given in Table 6.3-1. The SDCF is the EDE divided by the concentration of interest. The geometrical reduction factor for the IL vaults is 0.4. The fraction of the initial inventory of radionuclides remaining in the vaults at the various times after disposal, which takes into account radioactive decay and mobilization and transport in water, was calculated using the PORFLOW computer code.

Table 6.3-5 Intruder-based I-129 disposal limits for IL vaults - agriculture scenario at 20,000 years

Waste Form	Kd ml/g	Time of Assessment (yr)	Fraction Remaining[a]	Concentration Limit[b] ($\mu Ci/m^3$)	Inventory Limit[c] (Ci/vault)
Activated Carbon	600	20,000	0.502	6000	34

[a] Used 10,000 year inventory
[b] Limit on average concentration in disposed waste; obtained from Eq. 6.3-5
[c] Limit on inventory per vault; obtained from Eq. 6.3-4, assuming a vault volume of 5.7E3 m^3.

The results of the analysis are given in two forms, both of which are based on the dose limit for inadvertent intruders of 100 mrem per year. The first set of results is in the form of limits on average concentrations of radionuclides in the waste. The second set of results is in the form of limits on total activity of radionuclides in each vault.

The results in Table 6.3-5 may be interpreted as follows. The maximum dose would occur at the time after disposal at which the agriculture scenario first becomes credible, and the results at

20,000 years represent lower-bound estimates of limits on average concentrations and inventories of radionuclides in waste.

6.3.2 General Dose Analysis for Resident Scenario

Two bounding assumptions have been used in the dose analysis for the resident scenario for inadvertent intruders. In the first case, the intruder is assumed to reside in a home located immediately on top of an intact concrete roof or other engineered barrier above a disposal unit, and the scenario is assumed to be credible immediately following loss of active institutional control at 100 years after disposal. In the second case, the home is assumed to be located immediately on top of the waste in a disposal unit, but the scenario is assumed not to occur until the concrete roof and any other engineered barriers above the waste have lost their integrity and can be penetrated during excavation.

In both bounding cases for the resident scenario, the intruder is assumed not to excavate into the waste itself while constructing a home on the disposal site. Thus, the only exposure pathway of concern for this scenario is external exposure to photon-emitting radionuclides in the waste while residing in the home. The only differences between the two bounding cases are the time at which the scenario is assumed to become credible, as described above, and the amount of shielding between the source region (i.e., the waste) and the receptor location.

The resident scenario is potentially relevant at any time following the 100-year institutional control period until the agriculture scenario becomes credible. Once the agriculture scenario becomes credible, the resident exposure becomes irrelevant because the agriculture scenario includes the resident scenario.

The SDCFs obtained from the model for estimating dose to an inadvertent intruder for the resident scenario are summarized in Table 6.3-2 in the CSEW report (DOE, 1999b). For all units, the geometrical reduction factors are listed in Table 6.3-4 in the CSEW report (DOE, 1999b). The remainder of this section discusses application of the model represented by Equations 6.3-4 and 6.3-5 to the IL Vaults in E Area.

6.3.2.1 Analysis of Intermediate-Level Vaults

As described previously, the IL vaults will be constructed with a concrete roof of average thickness about 90 cm and a layer of uncontaminated grout above the waste of thickness about 90 cm. Thus, the total thickness of these engineered barriers is about 1.8 m, and this thickness of shielding would apply to the resident scenario for the IL vaults at 100 years after disposal when all engineered barriers are assumed to be intact and impenetrable by normal excavation procedures.

As described in Appendix C.3.3, the 1.8 m thickness of shielding in the IL vaults is sufficient to reduce the external dose to very low levels for any conceivable concentrations of photon-emitting radionuclides in the waste. Therefore, in the dose analysis for the IL vaults at 100 years after disposal, the conservative assumption is made that only the layer of uncontaminated grout above the waste is present to provide shielding. For purposes of this analysis, the thickness of the grout layer is assumed to be 100 cm. This value is slightly greater than the planned thickness and is intended to take into account the somewhat greater shielding provided by any metal waste containers and waste forms in the IL vaults compared with the shielding provided by soil-equivalent material.

The results of the dose analysis for the resident scenario at 100 years after disposal are given in Table 6.3-11. The results are calculated in the same manner as those for the agriculture scenario using Eqs. 6.3-4 and 6.3-5, and the SDCFs are those for 100 cm of shielding in Table 6.3-2. The fraction remaining was calculated using PORFLOW. The geometrical reduction factor of 0.4 was assumed (Table 6.3-4).

Table 6.3-11 Intruder-based I-129 disposal limits for IL vaults - resident scenario at 100 years

Waste Form	Kd ml/g	Time of Assessment (yr)	Fraction Remaining	Concentration Limit[a] (μCi/m^3)	Inventory Limit[b] (Ci/vault)
Activated Carbon	600	100	1.0E+00	[c]	[c]

[a] Limit on average concentration in disposed waste; obtained from Eq. 6.3-5
[b] Limit on inventory per vault; obtained from Eq. 6.3-4, assuming a vault volume of 5.7E4 m^3.
[c] EDE negligible with the 100 cm shielding of intact vault.

The results in Table 6.3-11 are expected to be quite pessimistic, and thus, the derived concentration and inventory limits are identified as worst-case conditions. As described above, the assumed thickness of shielding of 100 cm for these calculations greatly underestimates the amount of shielding that would be provided by an intact concrete roof and the uncontaminated layer of grout above the waste.

As described previously, the second bounding case for the resident scenario for the IL vaults is based on the assumption that the intruder's home is located immediately on top of exposed waste in a disposal unit, but that the excavation for the home does not penetrate into the waste itself, because the grout at the depth of the top layer of waste is still intact. Therefore, this variation of the resident scenario could not reasonably occur until the concrete roof above the vaults has lost its integrity and the layer of uncontaminated grout above the waste has weathered to soil-equivalent material. An analysis described previously in presenting the results for the agriculture scenario indicates that the earliest the second bounding case for the resident scenario could occur is about 10,000 years after disposal.

The results of the dose analysis for the resident scenario at 10,000 years after disposal are given in Table 6.3-12 and again are obtained using Equations 6.3-4 and 6.3-5. The SDCFs in this case are those for no shielding in Table 6.3-2. Only long-lived radionuclides are of concern at this time.

Table 6.3-12 Intruder-based I-129 disposal limits for IL vaults - resident scenario at 10,000 years

Waste Form	Kd ml/g	Time of Assessment (yr)	Fraction Remaining	Concentration Limit[a] (μCi/m^3)	Inventory Limit [b] (Ci/vault)
Activated Carbon	600	10,000	1.0E+00	1.8E5	1,000

[a] Limit on average concentration in disposed waste; obtained from Eq. 6.3-5
[b] Limit on inventory per vault; obtained from Eq. 6.3-4, assuming a vault volume of 5.7E4 m^3.

The assumption that residence on top of exposed waste could occur at 10,000 years after disposal may also be pessimistic for the IL vaults. Even if the gravel layer were exposed by this time, it presumably would be quite resistant to further erosion. Because the top of the gravel layer will be about 3.5 m above the top layer of waste and an excavation for a home is assumed to extend no more than 3 m below the ground surface, an excavation at 10,000 years probably would not extend to the depth of waste. The additional shielding provided by the remaining layer of uncontaminated material between the bottom of the excavation and the waste has not been taken into account in the dose analysis.

In contrast to the dose analysis for the agriculture scenario, there is no need to perform a dose analysis for the resident scenario at times after residence on top of exposed waste first becomes credible. At later times the top layer of waste presumably would begin to weather to soil-equivalent material and the agriculture scenario, which always results in a higher dose per unit concentration of radionuclides, then becomes the scenario of concern.

6.3.3 Dose Analysis for Post-Drilling Scenario

The post-drilling scenario is potentially relevant for any disposal units for which drilling into the waste may occur before the agriculture scenario becomes credible. In the IL vaults, the waste will be grouted, and drilling into the waste is not expected to be a credible occurrence until the grout essentially has weathered to soil-equivalent material, at which time the agriculture scenario becomes credible. Because the agriculture scenario always results in more restrictive disposal limits for radionuclides than the post-drilling scenario for the same time, the post-drilling scenario need not be considered further in the IL vaults.

6.4 Sensitivity and Uncertainty in Dose Models for Inadvertent Intruders

The sensitivity and uncertainty analysis for the IL Vaults is similar to that in the CSEW report. The CSEW report focused on six parameters. Those parameters and the factors of uncertainty for each of them are as follows:

Parameter	Factors of Uncertainty
Atmospheric mass loading of contaminated surface soil	Not applicable
Consumption of contaminated soil	1 order of magnitude
Exposure time for working in a garden	3

Exposure time for residing in a home	2
Fractions of initial radionuclide inventory remaining in the waste	For high Kd contaminants this is primarily a function of radioactive decay, so very little uncertainty
Plant-to-soil concentration factors	1 to 3 orders of magnitude.

The major difference between the CSEW report and this report is that this report only considers I-129 with varying K_ds. The most important factor in determining whether or not the WAC derived from dose analyses for inadvertent intruders are likely to be reasonable is the credibility of the assumed exposure scenarios, i.e., whether the assumed exposure scenarios reasonably could occur at a particular disposal facility, rather than any estimates of uncertainties in the results due to uncertainties in model parameters.

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SECTION 7

PERFORMANCE EVALUATION

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7. PERFORMANCE EVALUATION

The purpose of this waste-specific SA of the E-Area LLWF is to fulfill the DOE Order 435.1 requirement that such an assessment be prepared and maintained for any LLW disposal facility located at a DOE field site. In this chapter of the SA, a comparison of the SA results to DOE Order is provided and the utility of the results in developing operational limits is discussed. Ongoing or planned investigations that are needed in support of the SA process are also discussed.

7.1 Comparison of Results to Performance Objectives and Requirements

The performance objectives and assessment requirements of DOE Order 435.1 for LLW disposal are listed in Section 2.5. In essence these objective put forth dose limits for members of the public that are not to be exceeded through consideration of credible pathways. The requirements establish that impacts on water resources and inadvertent intruders are to be assessed.

For the groundwater impacts requirement, it has been determined that compliance with current, not proposed, EPA standards is required because of the interpretation of CERCLA regulations by the State of South Carolina. However, if and when EPA changes those standards, the inventory limits presented in this report must be recalculated.

To evaluate the performance of the E-Area LLWF with respect to protection of the public from releases to water, soil, plants, and animals and with respect to impacts on water resources, groundwater concentrations were estimated for a uniformly loaded vault and compared with the more restrictive of either allowable groundwater concentrations based on a 25 mrem/yr dose (the performance objective for protection of off-site members of the public from radionuclides released to any media but the atmosphere) or MCLs (the performance measure for impacts on water resources). Based on this comparison, inventory limits for the IL Vaults were developed (Section 5.1). Inventory limits resulting from atmospheric releases of radionuclides were determined to be inconsequential (Section 4.1.2). For inadvertent intruders, inventory limits were calculated and presented in Section 6, based on a comparison of estimated doses to intruders with the 100 mrem/yr limit on EDE for continuous exposure.

In this section, these calculated inventory limits are compared to the projected inventories for the IL Vaults. The results of these comparisons are presented in Table 7.1-1.

The inventory limit for a single IL Vault is presented in the second column of this table. It is the lowest limit calculated after consideration of all intruder scenarios, groundwater pathways, and air pathways for up to 10,000 years after closure of the facility. The third column identifies the limiting pathway, the intruder scenario, or groundwater or air pathway that provides this lowest limit. The fourth column lists the projected inventory of each waste form (from Appendix A) for the existing IL Vault. Finally, the fifth column in the table is the ratio of the inventory limit.

Table 7.1-1 IL Vaults: High-Concentration I-129 Waste Inventory Limits, Limiting Pathway, and Comparison to Projected Inventory

Waste Form	Inventory limit [a] Ci per vault	Limiting pathway [b]	Projected inventory for one IL Vault Total Ci	Ratio of inventory limit to projected inventory [c]
Activated Carbon	7.14E-2	gw	7.30E-2	0.98

[a] Inventory limit based on consideration of peak groundwater concentration outside 100-m buffer zone around disposal units (Section 5) and inadvertent intruder doses (Section 6).
[b] Identifies whether intruder scenario, groundwater ingestion pathway ("gw"), or air pathway is most restrictive with respect to developing inventory limits.
[c] A ratio that is one or greater indicates that the projected inventory is less than the estimated inventory limit.

The calculated inventory limit is slightly smaller than the projected inventory; thus, this facility does not satisfy the performance objectives. However, the projected inventories are highly uncertain. The actual future inventory may be less than the projected inventory for two reasons as follows:

1. Future site activities may diminish, thus reducing the amount of waste generated.
2. On average, I-129 concentrations for future activated carbon vessels may be less than the concentration used for projections. Activated carbon vessels already in the IL Vault have an average I-129 content of 4.8E-4 Ci per vessel. Vessel #9, awaiting disposal, was characterized at 7.11E-3 Ci. The higher value was used as an estimate for all future vessels. The projected inventory using a weighted average of the five vessels would be 2.53E-2 Ci versus the Table 7.1-1 value of 7.30E-2 Ci.

Even if the actual future inventory exceeds the inventory limit for the existing IL Vault, mitigating measures are available. Waste could be stored until the second IL Vault is constructed. Waste could be repackaged and sent to the LAW vault, because the Activated Carbon Vessels are not true intermediate-level waste; only the geometry of the waste prevents its direct disposal in the LAW vault.

7.2 Use of Special Analysis Results

The information in this section is identical to that in Section 7.2 of the CSEW report (DOE 1999b). A special addition in this report is an equation developed to help estimate the inventory limits for high-concentration I-129 waste forms that may have K_ds measured in the future. That equation was presented and discussed in Section 5.1 and is as follows:

$$\text{Inventory Limit (Ci/vault)} = 1.188\text{E-}4 * K_d \text{ (ml/g)} + 1.504\text{E-}6.$$

7.3 Further Work

The information in this section is identical to that in Section 7.3 of the CSEW report (DOE 1999b).

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SECTION 8

QUALITY ASSURANCE

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8. QUALITY ASSURANCE

The information in this section is identical to that in Section 8 of the CSEW report (DOE 1999b).

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SECTION 9

LIST OF PREPARERS

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9. LIST OF PREPARERS

The information in this section is identical to that in Section 9 of the CSEW report (DOE 1999b).

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SECTION 10

REFERENCES

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10. REFERENCES

The information in this section is identical to that in Section 10 of the CSEW report (DOE 1999b), except that additional references and newer revisions are added as follows:

Kaplan, D.I., S.M. Serkiz, and N.C. Bell. 1999. *I-129 Desorption from SRS Water Treatment Media from the Effluent Treatment Facility and the F-Area Groundwater Treatment Facility*, WSRC-TR-99-270, Westinghouse Savannah River Company, Aiken, South Carolina.

Liam, K.C., S.K. Roy, and D.O. Northwood. 1992. Chloride Ingress Measurements and Corrosion Potential Mapping Study of a 24-Year-Old Reinforced-Concrete Jetty Structure in a Tropical Marine-Environment, *Magazine of Concrete Research*, V44, N160 (Sep), ISSN: 0024-9831, pp. 205-215.

U.S. DOE. 1999b. *Special Analysis for Disposal of Cement-Stabilized Encapsulated Waste at the E-Area Low-Level Waste Facility*, WSRC-RP-99-00596, Westinghouse Savannah River Company, Aiken, South Carolina.

WSRC. 1999a. *Safety Analysis Report Savannah River Site Solid Waste Management Facility* (U), WSRC-SA-22, Rev.2, September 1999.

WSRC. 1999b. *WSRC 1S Savannah River Site Waste Acceptance Criteria* Manual, Procedure WAC 3.17 Low Level Radioactive Waste Acceptance Criteria, Rev. 2 (U), June 1999.

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APPENDIX A

PROJECTED INVENTORY FOR HIGH-CONCENTRATION I-129 WASTE

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Table A.1 Projected Inventory for High-Concentration I-129 Waste Considered for Disposal in the IL Vaults

Waste Form	Projected Inventory (Ci)[a]
Existing Activated Carbon Vessels in IL Vault	1.92E-3
Future Activated Carbon Vessels	7.11E-2
Total	7.30E-2

[a] Walliser, 1999.

REFERENCES

Walliser, S.A., Interoffice Memo SWD-ETF-99-078, December, 1999 – attached.

OSR 31-688 (Rev 11-20-97)
Stores: 26-8910.00

WESTINGHOUSE SAVANNAH RIVER COMPANY

INTEROFFICE MEMORANDUM

BNFL

December 15, 1999 SWD-ETF-99-078

To: Leonard Collard, 773-43A
Waste Disposal and Env. Develop

From: S.A. Walliser, 704-23H, 8-1862
ETF Facility Support

Subject: Projections of Resin and Carbon Wastes

The purpose of this memo is to formalize the projections of both GT-73 resin and activated carbon wastes which were contained in various email messages.

Activated Carbon

Carbon vessel #9 was sampled in January, 1998, for radionuclides for the purpose of revising/upgrading the carbon waste stream characterization. The I-129 concentration was reported as 301 pCi/g, resulting in an I-129 loading of 7.11E-03 Ci for the vessel. The details of this calculation are shown in Attachment 1.

The annual low level waste forecast for ETF has projected one spent carbon vessel per year. This results in a ten year inventory projection of 7.11E-02 Ci I-129. See Attachment 3.

Organic Removal System GT-73 Resin

The Organic Removal System, Mercury Removal Column #2, GT-73 resin was sampled July, 1998, for radionuclides for the purpose of upgrading the GT-73 resin waste stream characterization. The I-129 concentration was initially reported as 0.0483 pCi/g (GEL Lab lower limit of detection value); however, subsequent reanalysis indicated 36.3 pCi/g (SRT-ADS-99-1227). Using the SRTC value, this correlates to 3.71E-05 Ci I-129 per vessel. The sample results and calculations are shown in Attachment 2.

The low level waste forecast for ETF has projected three OR GT-73 vessel volumes every two year. This results in a ten year inventory projection of 5.57E-04 Ci I-129. See Attachment 3.

Ion Exchange System GT-73 Resin

The Ion Exchange GT-73 resin columns were not sampled up through 1998. Based on the configuration of the ETF process systems, ETF Engineering estimated that the IX GT-73 resin would only be subject to about 1/10th of the I-129 adsorbed by the carbon. Thus, the IX GT-73 I-129 concentration was estimated to be 3.6 pCi/g. This estimation has been subsequently confirmed with more recent sampling and analysis (see Attachment 2, Footnote #1). The 3.6 pCi/g concentration correlates to 5.77E-06 Ci I-129 per vessel.

The low level waste forecast for ETF included two IX GT-73 vessel volumes every two years. This results in a ten year inventory projection of 5.77E-05 Ci I-129. See Attachment 3.

Should you have any questions, please advise.

Attachments

Cc: N. Roddy
D. Sink
S. Wiggins
T. Lookabill
M. Birk
D. Collins
L. Rykken
T. Butcher
ETF Files

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December 10, 1999
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Attachment 1

ETF Carbon Vessel #9
Sampled: Jan 1998, SRS Site Sample Management Id 98037-1

Nuclide	Sample Results (pCi/g)	Calculated (Ci/vessel)
H-3	1690	3.99E-02
C-14	24.7	5.83E-04
Ni-59	11.5	2.71E-04
Tc-99	21.3	5.03E-04
I-129	301	7.11E-03
Cs-137	45.9	1.08E-03
Ba-137m	43.4	1.02E-03
U-233/234	1.57	3.71E-05
Np-237	4.03	9.51E-05
Pu-239/240	86	2.03E-03
Am-241	14.8	3.49E-04
U-238	2.98	7.04E-05
Pu-238	177	4.18E-03
Pu-241	239	5.64E-03
Pu-242	1.57	3.71E-05
Co-60	4.21	9.94E-05
Sr-90	11.8	2.79E-04
	TOTAL:	**6.33E-02**

Conversion Factors:
454 g/lb
1.00E+12 pCi/Ci

Carbon Vessel Weights:
70,000 lbs gross wt typical
18,000 lbs tare wt
52,000 lbs waste wt

Waste weight content consists of spent carbon, adsorbed organics, biological growth, and moisture.

Calculated by: S. A. Walliser, 6/1/99

For the purposes of waste forecasting and disposal, a carbon vessel is manifested as 1032 ft3.

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Attachment 2

ETF Organic Removal (OR), Mercury Removal Column #2 (GT-73 Resin)
Sampled: July 1998 (Documented in SWD-ETF-99-005)
And Estimated Ion Exchange (IX), Mercury Removal Column Radionuclides

Nuclide	Adjusted OR Sample Result (pCi/g)	OR Spent Resin (Ci/ft3)	Calculated OR Hg Col (Ci/vessel)	[2]Estimated IX Hg Col (Ci/vessel)
H-3	343	7.79E-06	3.50E-04	5.45E-04
C-14	33.6	7.63E-07	3.43E-05	5.34E-05
Ni-59	1.48	3.36E-08	1.51E-06	2.35E-06
Co-60	195	4.43E-06	1.99E-04	3.10E-04
Sr-90	2370	5.38E-05	2.42E-03	3.77E-03
Y-90	2370	5.38E-05	2.42E-03	3.77E-03
Tc-99	84	1.91E-06	8.58E-05	1.33E-04
I-129	*0.0483*[1]	*1.10E-09*	*4.93E-08*	*7.67E-08*
I-129 (reanalysis)	36.3	8.24E-07	3.71E-05	5.77E-06
Cs-137	10,100	2.29E-04	1.03E-02	1.60E-02
Ba-137m	9554.6	2.17E-04	9.76E-03	1.52E-02
Np-237	0.0439	9.97E-10	4.48E-08	6.98E-08
Pu-238	246	5.58E-06	2.51E-04	3.91E-04
Am-241	109	2.47E-06	1.11E-04	1.73E-04
Pu-241	5020	1.14E-04	5.13E-03	7.98E-03
U-233	8.84	2.01E-07	9.03E-06	1.40E-05
U-234	8.84	2.01E-07	9.03E-06	1.40E-05
U-235	1.45	3.29E-08	1.48E-06	2.30E-06
Pu-239	1050	2.38E-05	1.07E-03	1.67E-03
		TOTAL:	**3.22E-02**	**5.00E-02**

Conversion Factors:
454 g/lb
1.00E+12 pCi/Ci

Resin Density:
50 lb/ft3

OR Hg Col Resin Volume:
45 ft3

IX Hg Col Resin Volume:
70 ft3

1. IX GT-73 resin I-129 concentration is estimated to be 1/10th of the OR GT-73 value due to process configuration. Subsequent analysis by SRTC (ADS Id 3-134077) showed 3.13 pCi/g, thus confirming Engineering's original estimation.
Calculated by S. A. Walliser, 6/2/99, modified 12/14/99

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Attachment 3

ETF Waste Projection Summary
(Based on 1998 sampling data)

	Carbon	OR GT-73	IX GT-73
I-129 (pCi/g)	301	36.3	3.63
Waste Weight or Vol	52,000 lbs	45 ft3	70 ft3
Curies (I-129) per Vessel	7.11E-03	3.71E-05	5.77E-06
Expected Waste Generation Rate	1 vessel/year	3 vessel volumes every two years	2 vessel volumes every two years
Ten Year Projection (I-129 Ci)	7.11E-02	5.57E-04	5.77E-05

The density of damp GT-73 resin is 50 lb/ft3

APPENDIX B

COMPUTER CODES

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The information in this appendix is identical to that in Appendix B of the CSEW report (DOE 1999b).

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APPENDIX C

SUPPORTING DETAILS OF MODELS AND ASSUMPTIONS

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Appendix C provides details of models and assumptions that support the information provided in Sections 4 through 6 of the main body of this SA.

C.1 VADOSE ZONE MODELS

Vadose zone models were developed to analyze the release and transport of radionuclides from the waste facility to the aquifer.

C.1.1 Infiltration

Because Section C.1 is independent of the facility, it is identical to Section C.1 in the CSEW report (DOE 1999b).

C.2 SATURATED ZONE MODEL

Section C.2 discussing the saturated zone model is identical to Section C.2 in the CSEW report (DOE 1999b).

C.3 INTRUDER MODELS

Section C.3 discussing intruder models is identical to Section C.3 in the CSEW report (DOE 1999b); except that no screening was performed, only high-concentration I-129 wastes were considered, and the results are different. Parameters for the I-129 analysis were extracted from CSEW tables and are presented below. For clarification, Δ_s is the dry bulk density of soil (kg/m^3). The overall factor of EDE per unit concentration can be conveniently referred to as the scenario dose conversion factor (SCDF).

Table C.3-1 Radionuclides Considered in Dose Analyses for Off-site Individuals or Inadvertent Intruders

Radionuclide	Half-Life[a]	Applicable scenarios[b]
I-129	1.57E+07 yr	1,2,4

[a] Values from Kocher (1981).

[b] 1 = groundwater transport pathway, off-site individuals;
2 = agriculture scenario, inadvertent intruders;
3 = resident scenario, inadvertent intruders;
4 = post-drilling scenario, inadvertent intruders.

Table C.3-2 Internal Dose Conversion Factors (DCFs) for Ingestion and Inhalation of Radionuclides

Radionuclide	Ingestion DCF[a] Rem/μCi	Inhalation DCF[b] Rem/μCi
I-129	2.8E-01	1.8E-01

[a] Fifty-year EDEs from USDOE 1988; when values are given for more than one GI-tract absorption fraction, value corresponding to higher absorption fraction is adopted.
[b] Fifty-year EDEs from USDOE 1988; when more than one DCF is given for different lung clearance classes, the clearance class giving the highest DCF is selected, except as noted.

Table C.3-3 External Dose-Rate Conversion Factors for Radionuclides Uniformly Distributed in 15 Cm of Surface Soil

Radionuclide	Rem/yr per uCi/m^3 [a]
I-129	8.1E-06

[a] From Eckerman and Ryman (1993); EDE from external exposure per unit activity concentration in soil at distance of 1m from source region.

Table C.3-4 External Dose-Rate Conversion Factors for Radionuclides Uniformly Distributed in Infinite Thickness of Soil-Equivalent Material

Radionuclide	Dose-rate factor[a] No shielding Rem/yr per μCi/m^3	Dose-rate factor[b] 45 cm shielding Rem/yr per μCi/m^3	Dose-rate factor[b] 100 cm shielding Rem/yr per μCi/m^3
I-129	8.1E-06	---	---

[a] From Eckerman and Ryman (1993); EDE rates from external exposure per unit activity concentration in soil at distance of 1 m from source region.
[b] Represent EDE rates from external exposure per unit activity concentration in soil at distance of 1 m from source region; are based on calculations for monoenergetic photon sources (Kocher and Sjoreen 1985) and energies and intensities of photons emitted in decay of radionuclides (Kocher 1981).

Table C.3-5 Annual EDEs from Drinking Water Pathway Per Unit Concentration of Radionuclides in Water

Radionuclide	EDE rem/yr per μCi/L
I-129	2.0E+02

Table C.3-6 Elemental Plant-to-Soil Concentration Ratios in Vegetables

Element	B_v [a,b]
I	2.2E-02

[a] μCi/kg fresh weight in vegetation per μCi/kg dry weight in soil.

[b] Except as noted, values are based on concentration ratios reported on basis of dry weight of vegetation given in Fig. 2.2 of Baes et al. (1984) multiplied by a factor of 0.43 to convert to fresh weight of vegetation (Baes et al. 1984).

Table C.3-7 Annual EDEs from Vegetable Pathway Per Unit Concentration of Radionuclides in Exhumed Waste for Agriculture Scenario

Radionuclide	EDE (rem/yr per μCi/m^3)
I-129	7.9E-05

Table C.3-8 Annual EDEs from Soil Ingestion Pathway Per Unit Concentration of Radionuclides in Exhumed Waste for Agriculture Scenario

Radionuclide	EDE (rem/yr per μCi/m^3)
I-129	1.5E-06

Table C.3-9 Annual EDEs From External Exposure in Vegetable Garden Per Unit Concentration of Radionuclides in Exhumed Waste for Agriculture Scenario

Radionuclide	EDE (rem/yr per μCi/m^3)
I-129	1.6E-08

Table C.3-10 Annual EDEs from External Exposure in Home Per Unit Concentration of Radionuclides in Disposal Units for Agriculture Scenario

Radionuclide	EDE (rem/yr per μCi/m^3)
I-129	2.8E-06

Table C.3-11 Annual EDEs from Inhalation Exposure in Vegetable Garden Per Unit Concentration of Radionuclides in Exhumed Waste for Agriculture Scenario

Radionuclide	EDE (rem/yr per $\mu Ci/m^3$)
I-129	2.1E-10

Table C.3-12 Annual EDEs from Inhalation Exposure in Home Per Unit Concentration of Radionuclides in Disposal Units for Agriculture Scenario

Radionuclide	EDE (rem/yr per $\mu Ci/m^3$)
I-129	5.1E-09

Table C.3-13 Annual EDEs Per Unit Concentration of Radionuclides in Disposal Units from All Exposure Pathways for Agriculture Scenario

Radionuclide	EDE (rem/yr per $\mu Ci/m^3$)
I-129	8.4E-05

Table C.3-14 Annual EDEs Per Unit Concentration of Radionuclides in Disposal Units for Resident Scenario

	EDE (rem/yr per $\mu Ci/m^3$)		
Radionuclide	No Shielding [a]	45 cm shielding [b]	100 cm shielding [c]
I-129	2.8E-06	----	----

[a] Results apply to all disposal unit at times when engineered barriers which provide shielding above the waste are assumed to have lost their physical integrity.

[b] Results apply to LAW vaults at 100 years after facility closure, when the roofs of the vaults are assumed to be intact and residence on unshielded waste is not credible.

[c] Results apply to IL vaults at 100 years after facility closure, when the roofs of the vaults and uncontaminated grout layer over the waste are assumed to be intact and residence on unshielded waste is not credible.

Table C.3-15 Annual EDEs Per Unit Concentration of Radionuclides in Exhumed Waste for Post-Drilling Scenario

Radionuclide	EDE (rem/yr per $\mu Ci/m^3$)
I-129	8.1E-06

Table C.3-16 Summary of All Scenario Dose Conversion Factors (SDCF) for I-129 for Inadvertent Intruder Cases

SCENARIO	SDCF	DCF	uw	uv	us	ua	Biv	La	ug	us	fa		s	deltas
Offsite:Water	**2.0E+02**	0.28	730											
Ag:Vegetable	7.9E-05	0.28		90			2.2E-02					0.2		1400
Ag:Soil	1.5E-06	0.28			3.7E-02							0.2		1400
Ag:ExtGarden	1.6E-08	8.1E-06							0.01			0.2		
Ag:AirGarden	2.1E-10	0.18				8000		1.0E-07			0.01	0.2		1400
Ag:ExtHouse	2.8E-06	8.1E-06								0.5			0.7	
Ag:AirHouse	5.1E-09	0.18				8000		1.0E-08			0.5	1		1400
Ag:All	**8.4E-05**													
Res:ExtHouse	**2.8E-06**													
Ag:Subtotal-NoHouse	8.1E-05													
PostDrill:All	**8.1E-06**	same as Ag:SubtotalNoHouse, but soil mixing (fs) of 0.02 rather than 0.2												

Note: SDCF calculated by multiplying all nonzero factors, except that "deltas" is a nonzero divisor

Table C.3-17. Summary of Radionuclide-Independent Parameter Values Used in Dose Analyses for Off-Site Individuals and Inadvertent Intruders

Parameter description	Symbol	Parameter value
Consumption of contaminated drinking water[a]	U_w	730 L/year
Consumption of contaminated vegetables[b]	U_v	90 kg (fresh weight) per year
Density of soil[b]	Δ_s	1,400 kg/m^3
Dilution factor for mixing of exhumed waste with native soil in vegetable garden	f_s	0.2[c] 0.02[d]
Consumption of contaminated soil[b]	U_s	0.037 kg/year
Exposure times -		
working in garden[b]	U_g	1% per year
residing in home[e]	U_h	50% per year
Shielding factor for external exposure during indoor residence[e]	S	0.7
Air intake (breathing rate)[b]	U_a	8,000 m^3/year
Atmospheric mass loading of contaminated surface soil -	L_a	
working in garden[b]		10^{-7} kg/m^3
residing in home[c]		10^{-8} kg/m^3

[a] Parameter applies to exposure of off-site individuals.
[b] Parameter applies to agriculture and post-drilling scenarios for inadvertent intruders.
[c] Parameter applies to agriculture scenario for inadvertent intruders.
[d] Parameter applies to post-drilling scenario for inadvertent intruders.
[e] Parameter applies to agriculture and resident scenarios for inadvertent intruders.

APPENDIX D

VAULT DEGRADATION STUDY

NOTE OF EXPLANATION FOR APPENDIX D

Appendix D was prepared in 1993, at a time when two different types of IL vaults were planned: the ILNT vaults (intermediate-level non-tritium vaults), and the ILT vaults (intermediate-level tritium vaults). The design for the ILNT vaults has since been adopted for IL vaults, and thus the results of the degradation assessment for that type of vault was used for the IL vaults. The results of the degradation assessment for the LAW vaults remains applicable, because the design has not changed.

E-AREA VAULTS
VAULT DEGRADATION STUDY

FINAL REPORT

Prepared For:

Westinghouse Savannah River Company
Aiken, SC 29803

Prepared By
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September 30, 1993

EXECUTIVE SUMMARY

The primary focus of this study was to determine the possible rates of roof and wall failure and the times to structural collapse of the roof and walls of three vault designs: the Intermediate Level Non-Tritium (ILNT), Intermediate Level Tritium (ILT) and Low Activity Waste (LAW) Vaults at the Department of Energy's Savannah River Site near Aiken, South Carolina. Failure was defined as a loss of ability to divert soil water around the vault. Collapse was defined as the total loss of structural integrity of the vault. Failure and eventual collapse of the three vault types, results from concrete deterioration under stress, in the presence of corrosive soil water. Degradation rates for reinforced concrete were utilized, and the resultant changes in properties (such as strength, thickness, cracking and hydraulic conductivity) were evaluated. Baseline times to failure and collapse of the walls and roof components were modeled, and sensitivity analyses were conducted to provide boundaries on these estimated times. Thus, the goal of the project was to provide a bounding analysis of the time to roof and wall failure and potential collapse, rather than an actual prediction of the time to failure and collapse. The overall approach was to develop an executive model which linked various pre-existing models of degradation of reinforced concrete and to integrate that model with structural engineering models which estimate stress in the structure, for the bounding analysis of failure and collapse.

Degradation processes considered were magnesium and sulfate attack, calcium leaching, carbonation, and rebar corrosion due to both oxygen diffusion to the rebar (including breakdown of the passivating layer that initially prevents corrosion of rebar) and due to the "hydrogen evolution" reaction. Existing empirical models for the individual degradation processes were combined into a single model to create an overall model of the degradation of reinforced concrete. The state of stress in the concrete and rebar was calculated and the roof components and walls fractured in order to eliminate excessive stress which cannot be borne by the degraded structure. Crack aperture and spacing were computed and used to estimate hydraulic conductivity.

For each type of vault, a sensitivity analysis was performed to bound the predictions. After an initial rough sensitivity analysis on a large number of factors, six factors were selected for detailed sensitivity analysis: rate of rebar corrosion due to the "hydrogen evolution" reaction, rebar diameter, depth of concrete cover over the rebar, size of AASHTO "bridge" beams used to support the vault roof in the LAW vault design, and depth of soil cover over the vaults, and concrete strength.

The ILNT Vault design consists of 7 rectangular cells, each approximately 48.5' long by 27' wide by 29.75' high. The ILT is a similar design, the main differences being that it consists of only 2 cells and utilizes a slightly thicker roof. The LAW vault consists of 4 cells, each approximately 145' x 53' x 26'. It utilizes a significantly different design in that AASHTO "bridge" beams are used to support the roof span. Baseline times to failure and collapse for the ILNT vault were 570 and 1,045 years, respectively. The thicker roof and two-cell design of the ILT vault result in longer times to failure and collapse for the ILT vault; 790 and 1,300 years respectively. For the LAW vault, failure and collapse are predicted to occur in 1,420 and 3,100 years. The following table summarizes the baseline results for each vault.

Summary of Baseline Results

Vault	Cracks Penetrate Roof/Failure (years)	Cracks Penetrate Walls (Mid-Height) (years)	Roof Collapse (years)
ILNT	570	800	1,045
ILT	790	1,080	1,300
LAWV	1,420	2,235	3,100

Sensitivity analysis indicated that the rate of rebar corrosion due to the hydrogen evolution reaction is the most critical and uncertain model parameter. Variation within the bounds of acceptable values reported in the literature can result in the times to failure and collapse varying hundreds to thousands of years. For example, for the ILNT vault, the time to failure varied from 285 years to 2,775 years, based on variation in the hydrogen evolution corrosion rates. Similarly, the time to collapse varied from 525 years to beyond the 3,000-year duration of the simulation for the ILNT vault.

Variation in depth of concrete cover over rebar and in concrete strength within design constraints resulted in variation in times to failure and collapse of less than 100 years. Variation in depth of soil cover within design constraints resulted in variation in times to failure and collapse on the order of 100 to 400 years. Changing the rebar diameter has the potential to significantly impact the longevity of the vaults. For example, changing the bar designation by 1 (for example from #8 to #7 or to #9) changes the time to failure and collapse on the order of 300 to 400 years. Changing the size of AASHTO beams has a similar impact on the time to collapse of the LAW vault. Utilizing a smaller beam, however, would result in cracks penetrating the vault (i.e., failure) immediately upon soil loading.

This study has combined pre-existing models for the degradation of reinforced concrete with proven structural engineering models to create a performance assessment code capable predicting the time of failure (loss of ability to divert water) and collapse (loss of structural integrity) of buried concrete vaults. This code can also be used to estimate the impact of changes in design parameters on the longevity of reinforced concrete structures, and therefore has potential for application as a design aid tool for below-ground storage facilities. The current mandate at DOE facilities to move in the direction of below-ground disposal in concrete-engineered structures makes this code a potentially important performance assessment tool.

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1. INTRODUCTION

The E-Area Vaults (EAV), which are the focus of this study, are located at the Savannah River Site (SRS) in South Carolina. The EAV designs which will be discussed in this report are the Intermediate Level Non-Tritium (ILNT), Intermediate Level Tritium (HM and Low Activity Waste (LAW) Vaults. Westinghouse Savannah River Company (WSRC) operates this site and is currently developing a Radiological Performance Assessment (RPA) for the EAV. The vault degradation study is a supporting study for this RPA.

The EAV site is located on a 200-acre site immediately north of Building 643-7E at the SRS. The original SRS Solid Waste Disposal Facility (SVIDF) and the added EAV site are centrally located between the two chemical separations areas near the center of the SRS, between Upper Three Runs Creek on the north and Four Mile Creek on the south. Of this 200 acre tract, only 100 acres have been developed at this time. The nearest site boundary to the SWDF is about seven miles to the west. The SWDF is in a relatively level highland region of the SRS at about 300 ft above sea level.

The E-Area Vaults are reinforced concrete structures intended for below ground storage of low-activity and intermediate-level wastes. Each of the EAV designs are intended to house designated waste types. The LAW vaults, which are located at a separate facility from the ILT and ILNT vaults, are designed to receive and store low-activity waste radiating less than 200 mR/hr at 5 cm from an unshielded container and containing only incidental quantities of tritium. One section of the Intermediate Level facility is designated as the ILNT vault and receives waste radiating greater than 200 mR/hr at 5 cm in engineered metal containers. The remaining section is designated as the ILT vault and receives tritium-bearing waste contained in engineered metal containers or as overpacked tritium crucibles with most of the tritium removed. These two vault sections are adjacently located, share waste package handling equipment and are to be closed as one facility. The LAW vault facility will be closed separately. A third facility, also a part of the EAV Project, designated as the Long-Lived Waste Storage Building (LLWSB) has not been considered as part of this degradation study.

Closure of the vaults will be via below ground burial under about 8 feet of soil cover. The placement of the soil cover and soil backfill around the vaults will result in loading of the roof and walls of each unit. Chemical attack on the buried reinforced concrete will weaken the concrete, and the roof and walls of each vault type could be expected to fail and collapse over time. Failure is defined as a loss of ability to divert water around the vault. Degradation of concrete by sulfate attack can cause thinning, calcium hydroxide leaching results in weakening of the concrete, carbonation lowers the pH of the matrix-bound water, and oxic ("oxygen") and anoxic ("hydrogen evolution") rebar corrosion weakens the reinforced concrete mass. Failure of the vault would result in infiltrating ground water entering the interior of the vault rather than being diverted around its exterior.

INTERA's approach to this performance assessment problem for the E-Area Vaults has been to construct a mathematical model which integrates structural loading calculations with chemical degradation calculations. The model runs on a PC-platform and utilizes, as subroutines, pre-existing empirical models for the chemical degradation calculations, and an American Concrete Institute code for the design of reinforced concrete structures to calculate the state of stress within the structure. Adopting this modeling approach facilitates sensitivity analyses on different design components of the vaults.

This report presents the chemical degradation mechanisms which have been modeled for degradation of the concrete of each of the vault designs, describes the structural design model and the approach for integrating these models into one code, and finally, presents the results of the performance assessment calculations on the three vaults types for baseline (base case) and variant configurations of several of the design components. Further work which will likely be accomplished under a separate task will include evaluating the performance of the vault floors for the three vault designs, and extending the sensitivity analyses beyond six parameters.

2. DESCRIPTION OF THE CLOSED ILT, ILNT AND LAW VAULTS

The EAV Project consists of three types of facilities to house four designated waste types and the necessary roadways to allow waste container delivery. This section describes in brief the three vault types.

2.1 INTERMEDIATE-LEVEL VAULTS

The intermediate-level vaults consist of two separate, subsurface reinforced concrete vault structures. The individual vaults are adjacently located, share a similar design, and are closed as a single unit. The vaults are identified as the Intermediate Level Tritium (ILT Vault, and the Intermediate Level Non-tritium (ILNT) Vault.

2.1.1 ILNT Vaults

Each ILNT Vault consists of seven cells or subdivided sections within the vault structure (Figure 1) and provides a total of approximately 200,000 ft^3 of waste storage capacity. The vaults are subsurface concrete structures approximately 189 ft long, 48.5 ft wide, and 29.75 ft deep. Exterior end walls are 2 1/2 ft thick, side walls are 2 ft thick, and interior walls (between the cells) are 1 1/2ft thick. All walls are structurally mated to a base slab which is approximately 2 1/2ft thick and extends past the outside of the exterior walls approximately 2 ft. The base slab rests on two layers of crushed stone placed on the compacted subsurface. The crushed stone drains to a collection sump to prevent a positive water head against the vault exterior.

Concrete is reinforced with deformed steel bars. All concrete construction joints are located at defined control joints with no horizontal joints in any vertical wall. All concrete joints include a waterstop seal which is continuous around all comers and intersections. All exterior concrete surfaces exposed to soil are coated with a coal tar-based waterproofing.

2.1.2 ILT Vaults

Each ILT Vault consists of two cells or subdivided sections within the vault structure (Figure 2) and provides approximately 57,000 ft^3 of waste storage capacity. One cell will in most cases be fitted with a silo system to permit the disposal of tritium crucibles. The IILT Vaults are structurally very similar to the ILNT, with slight differences such as wall height and thickness of the (proposed) roof slab. The ILT Vaults are approximately 57 feet long, 48.5 ft wide, and 28.5 feet deep. Wall arrangement, slab and slab base, and concrete are all identical for the two-cell. configuration ILT vault and the seven-cell configuration ILNT vault.

2.2 LAW VAULT

Each LAW Vaults consists of either two or three major subdivisions, or modules. Each module provides approximately 566,500 ft^3 storage capacity and will accommodate more than 4,OOO B-25 boxes. Figure 3 illustrates one module of a LAW Vault. Each module is approximately 214.5 ft long and 145 ft wide. Height of the vaults varies from approximately 26 to 27 feet. End, side, and interior walls of each module are all 2 ft thick. All walls are structurally mated to a 30-inch footer that is continuous under all cells in each module.

A reinforced concrete roof is supported by prestressed, concrete beams. The beams run between each wall the length of the vault. The end walls of each module have recessed beam seats to support a beam end, and the interior walls are equipped with bearing pads allowing beam ends to rest on the wall. The beams rest on elastomeric bearings which allow the bases of the beams to move towards each other as soil load and progressive deterioration of the structure causes the roof system to bend.

The slightly peaked roof is composed of 3 1/2-inch thick, prestressed, concrete deck panels installed directly on the roof beams providing a base for a 16-inch, cast-in-place roof slab. The roof slab has 2-in. wide expansion joints between module walls. Each expansion joint has flashing installed to provide waterproofing. The roof slab is covered with a bonded-in-place layer of fiberboard insulation and a layer of waterproof membrane roofing.

2.3 VAULT CLOSURE

Final closure of the vaults consists of placing an earthen cover with an engineered clay cap over the entire 21-vault area. The final closure cap will consist of a 2-foot thick compacted clay layer, on top of which will be a clay geomembrane or clay/geotextile composite. This will be overlain with a 1-foot thick granular drainage layer. Above the drainage layer will be a geotextile filter fabric. The uppermost layer of the closure cap will be a 2-foot thick topsoil cover. The slope of each of these layers will be 3 % over the ILNT and ILT Vaults, and 3 % or 4.3 % (depending on location) over the LAW Vaults. The total thickness of the soil layer will be between 8.5 and 9 ft. The "final closure cap" thus accounts for 5 ft of this thickness. The remaining volume will utilize compacted fill material. In addition, in order to reduce the hydraulic conductivity of the layered soil/vault system, a clay layer will be placed immediately adjacent to the vault roofs.

3. MODELS OF CHEMICAL DEGRADATION AND STRUCTURAL ANALYSIS

The selection of chemical degradation mechanisms for concrete was based on a process of eliminating mechanisms which demonstrated little or no effect under chemical conditions of the soil or concrete mix. The chemical degradation models which were included in the assessment were: $S0_4$ and Mg attack, $Ca(OH)_2$ leaching, carbonation, and rebar corrosion in oxic and anoxic conditions. Below we have presented the models for chemical degradation processes, some empirical and some analytic, and have provided a description of the attack mechanisms for which the models were derived. These mechanisms have been modeled independently. For example, thinning of the concrete surface will not result in an increased rate of reinforcing steel corrosion due to faster diffusion of oxygen through the decreased cover. In addition, the structural analysis modeling is described.

3.1 CHEMICAL ATTACK

3.1.1 Sulfate and Magnesium Attack

Sulfate and magnesium are naturally occurring elements at the Savannah River Site, input to the soil water from rainfall and weathering of rock minerals. Sulfate reacts with tricalcium aluminate (C_3A) to form calcium aluminum sulfates leading to expansion and cracking of the surface of the concrete (Walton et al., 1990). A related problem is the reaction of magnesium with the cement to form Brucite [$Mg(OH)_2$]. As the concrete cracks, its hydraulic conductivity increases, and water penetrates more easily into the interior, accelerating the deterioration of the concrete. Sulfate attack also results in a progressive loss of strength and mass due to deterioration in the cohesiveness of the cement hydration products. The reaction products have considerably greater volume than the reactants. This causes the expansion of the concrete which, in turn, results in cracking, spalling, and loss of strength. In addition, formation of gypsum causes a deterioration of the cement paste which results in a reduction in stiffness and strength, followed by more expansion, cracking, and loss of cohesiveness. Empirical studies indicate that the rate of attack by magnesium sulfate is twice that of sodium sulfate, and that the rate of attack is reduced by low water to cement ratio and by low C_3A content. The rate of surface loss due to sulfate attack was calculated according to:

$$X = 0.55Cs(C_{Mg} + C_{S04})\,t \;,$$

where:

X	=	distance of corrosion into concrete (cm),
C_s	=	C_3A concentration in solid (mole/cm),
C_{Mg}	=	Mg concentration in solution (mole/cm^3),
C_{SO4}	=	S04concentration in solution (mole/cm^3), and
t	=	time (s).

3.1.2 Alkali and Calcium Hydroxide Leaching

When concrete is exposed to water, constituents in the concrete are leached. Alkalis are leached first, followed by calcium hydroxide. This process can be described in four stages:

1. Initially, the pH of standard concrete is approximately 13 due to the presence of alkali metal oxides and hydroxides. These alkali metals leach first.

2. After the alkali metals are leached, the pH is controlled at 12.5 by solid calcium hydroxide. Free (not bound by C-S-H gel) calcium hydroxide is leached first.

3. Following loss of free calcium hydroxide, calcium hydroxide is leached at a slower rate from the C-S-H gel. The C-S-H gel dissolves incongruously, while the pH drops to 10.5 and the calcium to silicon ratio drops to 0.85.

4. The pH is held to 10.5 by congruent dissolution of the C-S-H gel.

The loss of calcium results in a decrease in strength of approximately 1.5 % for every I% loss of total calcium content. The rate of calcium hydroxide leaching depends primarily on the flow of water through the concrete, but also on diffusion into the surrounding geology, and diffusion across a reaction zone in the concrete. Advective transport of leached calcium hydroxide from the concrete structure will dominate only under high rates of groundwater' flow, and preferential flow of groundwater through the structure.

Atkinson and Hearne (1984) applied a shrinking core model to calcium hydroxide leaching. This model assumes that removal of calcium from the exterior of the concrete is rapid relative to movement of calcium through the concrete. Thus, leaching is controlled by conditions in the concrete and properties of the concrete, and so this process is referred to as "concrete-controlled leaching". As an alternative approach, Atkinson and Hearne also developed a leach model controlled by the surrounding geology ("geology-controlled leaching"). This model uses an equation for diffusion from a fixed concentration into a semi-infinite domain, with concentrations described by an error function (as in Crank, 1975), and allows for an analytic solution of the amount of calcium lost in a given amount of time. Both models predict that it will take over 1,000 years before calcium hydroxide leaching penetrates the upper 0.05 cm of the concrete. Both analytic models have been added to the degradation model. The equations used to approximate concrete-controlled and geology-controlled leaching, respectively, are:

$$X_C = \left[2D_i \frac{C_i - C_{gw}}{C} t \right]^{1/2}$$

and

$$X_G = 2\phi \frac{C_i - C_{gw}}{C_s}\left(\frac{R_d D_B t}{\pi}\right)^{1/2},$$

where,

X_C	=	depth of leach penetration due to concrete-controlled leaching (cm),
X_G	=	depth of leach penetration due to geology-controlled leaching (cm),
Di	=	intrinsic diffusion coefficient of Call in concrete (cm^2/s),
Ci	=	Call concentration in concrete pore water (mole/cm),
C_{gw}	=	Call concentration in ground/soil water ($mole/cm^3$),
C_s	=	bulk Call concentration in concrete solid ($mole/cm^3$),
ϕ	=	porosity of soil (unitless),
R_d	=	retardation coefficient (unitless), and
D_R	=	effective dispersivity/diffusivity of Call in the surrounding geologic material (cm/s).

A conservative estimate of the depth of leach penetration was obtained by summing Xc and X_G.

3.1.3 Carbonation

Carbonation is the reaction of carbon dioxide with cement to form calcium carbonate according to the reaction,

$$Ca(OH)_2 + H_20 + C0_2 => CaC0_3 + 2H_20 .$$

Sources of carbon dioxide are atmospheric gases and soil gases. Carbonation occurs most aggressively when the concrete is less than fully saturated with water, allowing $C0_2$ to diffuse through the air space in the concrete up to the reaction front within the concrete. At the reaction front, $C0_2$ dissolves in pore water and combines with calcium to precipitate calcium carbonate. From Walton et al. (1990), the depth of carbonation is proportional to the square root of time as shown in the equation below. The rate of carbonation depends on the moisture content of the concrete and its relative humidity, and ultimately on the type of cement used in the concrete mix.

Carbonation does not render the concrete less durable. Some fully-carbonated Roman concretes have survived to modem times. Shrinkage of the concrete may occur with carbonation as will a drop in the pH of the pore water. Carbonation of hydrated Portland-cement pastes also results in reduced hydraulic conductivity and increased hardness (Verbeck, 1958). The pH shift can be from over 12 to about 8. At this lower pH, enhanced corrosion of steel reinforcing in the concrete may occur.

The rate of carbonation is dependent upon water saturation or relative humidity of the concrete. As relative humidity increases from 0 to 100%, the rate of carbonation passes through a maximum. Since water is required in the carbonation reaction, partially saturated conditions promote the reaction of $C0_2$ and $Ca(OH)_2$ to form $CaCO_3$, however increasing the water content above that required for this reaction to proceed will slow the diffusion rate Of $C0_2$ through the concrete and limit the carbonation reaction. Typical subsurface environments approach 100% relative humidity, resulting in a water saturated concrete matrix. Therefore slow rates of carbonation are commonly found. The following analytic expression was employed for estimating carbonation rate in the degradation model:

$$X = \left(2D_i \frac{C_{gw}}{C_g} t \right)^{1/2},$$

where,

X	=	depth of penetration of carbonation (cm)
Di	=	intrinsic diffusion coefficient of Ca^{++} in concrete (cm/s)
C_{gw}	=	total inorganic carbon in ground water or soil moisture (mole/cm^3)
C_g	=	$Ca(OH)_2$ bulk concentration in concrete solid (mole/cm^3) and
t	=	time (s)

Inherent in the use of this expression is the assumption that the concrete is water-saturated, and that the concrete is in direct contact with moisture containing a constant concentration of dissolved inorganic carbon.

3.1.4 Rebar corrosion

Corrosion of steel reinforcement results in a loss of strength due to loss of cross-sectional area of the rebar. In addition, a reinforced-concrete structure may suffer structural damage due to the loss of the bond between steel and concrete. Corrosion of the rebar produces a reaction product of greater volume than the rebar. Since the concrete surrounding the reinforcement prevents free expansion, this expansion exerts pressure on the concrete, and thus causes cracking and potentially spalling of the concrete structure, with consequent loss of strength. In the alkaline environment of standard concrete (low alkaline specialty concrete is used for the EAV construction), the rebar is protected from corrosion by the formation of a passivating layer around the rebar. This passivating layer, however, may be destroyed by the diffusion of chloride ions to the embedded steel (i.e., depassivation). Water-to cement ratio and depth of concrete cover over the rebar are the most important factors in concrete construction that effect the time to depassivation. In the corrosion reaction, oxygen is electrochemically reduced and iron electrochemically oxidized, followed by conversion of the iron to iron oxides. The reaction rate is generally limited by diffusion of oxygen through the concrete to the rebar, with oxygen diffusion increasing over time as processes, such as calcium hydroxide leaching and sulfate attack, decrease the diffusion limiting concrete cover over the rebar.

Thus, the corrosion of reinforcing steel due to oxygen diffusion occurs in two steps. First, the passivating layer must be broken down before the onset of corrosion. The time to onset of corrosion was approximated by:

$$t_c = \frac{129 X_c^{1.22}}{WCR * Cl^{0.42}},$$

where,

t_c	=	time to onset of corrosion (yr),
X_c	=	thickness of concrete over rebar (inches),

WCR = water-cement ratio in concrete (kg/kg), and
Cl = chloride ion concentration in groundwater (ppm).

The reaction then proceeds, with a loss of reinforcing steel volume approximated by:

$$\%\ \text{Rebar Remaining} = 100\left(1 - \frac{4*9.4\left(\frac{cm^3}{mole}\right)sD_iC_s(t-t_c)}{\pi d^2 \Delta X}\right),$$

where,

s	=	spacing between reinforcement bars
Di	=	oxygen diffusion coefficient in con
C_{gw}	=	oxygen concentration in groundwater
t	=	time (s),
d	=	diameter of rebar (cm), and
ΔX	=	depth of rebar below surface (in).

Another mechanism of reinforcing steel corrosion is via the hydrogen evolution reaction. In this mechanism, H^+ ion from the water molecule is used as the source of oxidant for corrosion. H_2 is a by-product of this reaction. If we assume a low, constant rate of hydrogen evolution corrosion (i.e., a number from the low end of the literature range, is adopted), then the relative volume of steel remaining is: where,

$$\frac{V_{H_2}}{V_{ini}} = \frac{2at - d^2}{d^2}$$

a	=	corrosion rate from hydrogen evolution reaction (cm/yr),
t	=	time (yr), and
d	=	diameter of rebar (cm).
V_{H2}	=	volume of steel after H_2 corrosion
V_{ini}	=	initial volume of steel

Literature review of hydrogen evolution corrosion rates indicated a pH-dependence in the reaction rate. In the high pH range of typical concrete, the reaction rate is on the order of 1.5E-4 to lE-5 cm/yr. If the pH drops below approximately 9, the reaction rate increases to values on the order of lE-3 to lE-4 cm/yr.

A bounding analysis for corrosion will be utilized by combining the rates due to oxygen-based corrosion and hydrogen evolution corrosion.

3.1.5 Vault Interiors

The degradation mechanisms that were considered for the walls and roof in contact with site soil are: Mg + SO_4 attack, Ca(OH)2 leaching, concrete carbonation, and oxic and anoxic corrosion of the re-bar. Several of these mechanisms will not operate under the conditions anticipated inside the vaults or will occur so slowly that their net effect over the life of the vaults will be insignificant. Only anoxic ("hydrogen evolution") corrosion is anticipated as significant degradation process originating inside the vault, as discussed below.

Magnesium and sulfate attack requires a source of dissolved Mg andSO_4in contact with the concrete such as would be provided by a moist soil. There is no continuous source of Mg and SO_4 in contact with the concrete in the vault interior, and therefore this mechanism is not anticipated to operate.

Two forms of calcium hydroxide leaching were considered: concrete controlled and geology controlled leaching. The concrete controlled leaching mechanism assumed a zero-concentration boundary condition at the surface of the concrete, a condition which would require ground water to flow over the concrete surface and "sweep" the calcium away from the surface as it diffuses out of the concrete. Inside the vaults, during the period of performance prior to collapse, there is no recognizable mechanism to create this zero-concentration boundary. As a result, a chemical diffusion gradient from the interior of the concrete towards the concrete surface will not be established and diffusion will not occur.

Geology controlled leaching assumes that a concentration gradient can be established into the (soil) material adjacent to the concrete. This is physically impossible in the LAW vault because of the lack of in-filling material and in the case of the ILT and ILNT vaults, where cement grout will contact the walls, the calcium concentration in the grout pore water will be identical to that in the concrete at all times. These conditions prevent a concentration gradient from forming outwards away from the concrete.

Concrete carbonation occurs in the presence of dissolved carbonate and calcium in the pore water of the concrete. Leaching of calcium hydroxide provides a source of calcium and diffusion of carbonate ion from soil water in contact with the concrete provides a source of carbonate. The carbonate in the soil water is replenished from dissolution of CO_2 gas from the soil air. Inside the LAW vault, the air space will contain CO_2, although most likely at concentrations much less than in a biologically-active soil; differences of one to two orders of magnitude would be a reasonable estimate. Carbonation would most likely occur, however with only atmospheric levels of CO_2 driving the reaction, the carbonation front would advance at a much slower rate than for the outer surfaces of the vaults. From the empirical relationship that INTERA has been using to describe carbonation, a slowing of the movement of the carbonation front by an order of magnitude would be possible.

Corrosion of the reinforcing bar in concrete under oxygenated conditions requires an initial depassivation of the steel surface. The mechanism that has been invoked in our modeling relies on diffusion of chloride to the passivating layer. Depassivation is followed by oxidation of the exposed steel. The interior of the vaults does not provide a source of chloride for the depassivation mechanism. Degradation modeling of the interior of the vaults should therefore not include oxic corrosion of rebar, unless the concrete mix is such that the pH of the concrete is below 9.

Anoxic corrosion of rebar will occur in the presence of moisture in the concrete. Since water-saturated concrete has been assumed for the modeling of degradation, this mechanism would proceed at a rate approximately the same as for the exterior surfaces of the vault. Adjustments to the rate caused by a decrease in pH at the corroding surface following carbonation of the local concrete will not be required.

In summary, the dominant degradation mechanism for the interior surfaces of the vaults will likely be anoxic corrosion of re-bar. Carbonation is also likely to occur, however, the rate of advance of the carbonation front will be significantly less than for exterior surfaces. The effect of carbonation on anoxic corrosion will likely not be an important consideration.

3.2 STRUCTURAIJENGINEERING ANALYSIS

The RCPC.DHelper models (Furlong, 1991) used as the basis for the structural analysis portion of this study are available commercially through the American Concrete Institute. Software Sales Department. The programs have been in use for the past 4 years by approximately 300 engineering offices. The programs are intended to serve as a design aid in accordance with governing design documents, the principle one of which is the Building Code of the American Concrete Institute ACI 319-89. The Building Code is a strength design document with considerations for serviceability, but the major consideration for design is the limit strength of reinforced concrete members. Consequently, the computer design aids focus on decisions related to strength design instead of service load performance.

Strength design employs results from elastic analyses of frame response to the many different types and configurations of load that concrete structures support. An analytic routine known as the Portland Cement Association Two-Cycle Method is used for the interpretation of worst effects from pattern loading on beams. The analytic tools in RCPC.DHelper are just as appropriate for serviceability analyses as for strength design. The RCPC.DHelper programs apply required load factors and incorporate appropriate reliability factors in the logic required for design. These programs were modified to bypass load factors and reliability factors in order simply to use response to service load forces (load and reliability factors = 1) for estimates of service load stress in steel reinforcement and shear stress in concrete slabs. Steel stress was computed assuming that the concrete had cracked.

The program most appropriate for Vault Study is the Continuous Beam program in RCPC.DHelper. That program was prepared for design of floor beams in two-dimensional rigid frames. The Vault study involved two structures that consisted of roof slabs cast as rigid and monolithic with supporting walls. The structure represented by a unit width of wall and roof slab is a two-dimensional rigid frame. Distances between supports were adjusted such that the actual clear distances between faces of framing elements remained the same as those in the finished structure.

3.2.1 Application to the ILNT/ILT Vaults

Because the ILNT and ILT vaults are virtually identical in their design, the same approach was used to analyze the two structures. The only changes required were changes in input parameters such as height of the structure and roof thickness. The structures were represented by a 1-ft wide span of walls and roof in the direction of maximum stress. The direction of maximum stress in the short direction of each cell, or, for example, along the 189-ft length of the ILNT vault. Hand calculations indicated that this approach is accurate to within approximately 3% of the full 2-way slab analysis (Furlong, 1993). Parameter values were selected to correspond to the respective height, thickness, amount of rebar, etc. in the walls and roof of each vault.

Stress in concrete and rebar was computed at the locations which experience the maximum stress. Maximum stress occurs over the walls, in the exterior face rebar, and at midspan, in the interior face rebar (Figure 4). After the stress in the rebar was calculated, the roof components and walls may fracture in order to eliminate excessive stress which cannot be borne by the degraded structure. When the stress in the rebar at a particular location exceeds 40 ksi, cracks are assumed to penetrate the concrete. The approach to the calculation of stress in rebar assumes that the concrete has cracked. Crack width and spacing were computed as functions of the distance between the neutral axis[1] and the lower face of the concrete, the distance between the neutral axis[1] and the center of the reinforcing steel, the diameter of the reinforcing steel, the concrete cover over the reinforcing steel, and the strain on the reinforcing steel.

When the stress in the rebar at a particular location reaches the yield strength of the rebar (60 ksi), the rebar will yield. In most cells, yield strength is reached first at the midspan region. Excess moment is then transferred to other regions in the cell. In the case of the midspan region reaching yield strength first, excess moment is transferred to the regions over the walls. This, in turn, increases the stress levels in the rebar over the walls. When the rebar reaches its yield strength at all three locations, a "hinge" is created. This will allow the roof to sag, and it is presumed that structural integrity will be lost at this point. Therefore, the point in time at which this occurs has been defined as the time of collapse. This process can be summarized as follows:

1. Rebar at center of span reaches yield strength.
2. Excess moment (and corresponding stress) transferred to region over walls.
3. Rebar over walls reaches yield strength, resulting in severe cracking and collapse.

For cells 3, 4, and 5 of the ILNT vault, the rebar reaches yield strength in the regions over the walls before reaching yield strength at midspan. In this case, the order is reversed:

1. Rebar over walls reaches yield strength.
2. Excess moment (and corresponding stress) transferred to midspan.
3. Rebar at midspan reaches yield strength, resulting in severe cracking and collapse.

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[1]When a slab deforms under loading, part of the slab will be in compression and part of the slab will be in tension (e.g., at mid-span, the upper portion of the slab is in compression, and the lower portion in tension). The neutral axis is the location in the slab where compression changes to tension; it is therefore an axis of zero strain.

3.2.2 Application to the LAW Vault

The 3" thick prestressed slabs in the LAW Vault roof design serve to hold the cast-in-place slab, and are therefore ignored in subsequent calculations. The soil and self weight (of the slab and the AASHTO beams) will cause the beams to move on the elastomeric bearings. As the beams move, the upper ends of the precast girders remain separated by a fixed distance at the slab atop the girders (Figure 5). Only the bases of the beams move toward each other, leaving at the end of each beam an angle of rotation each side of the supporting wall. The angle of rotation remains essentially constant as long as the flexural stiffness of the girders remains constant under soil loading. Based upon the soil load and self load of the slab and beams, a curvature (in the roof, over the walls) of 0.35 radians/inch was calculated. This will result in a stress of 2.8 ksi in the concrete, sufficient to crack the concrete. The curvature was then used to calculate the moment in the slab, and stresses in the cracked concrete and rebar. In the]LAW Vault design, the stress level in the rebar increases relatively slowly as the structure degrades, and generally does not reach the 40-ksi limit. Therefore, the depth of the neutral axis was calculated in order to approximate the depth of crack penetration. As the structure degrades, the neutral axis, and therefore the cracks, penetrate further into the concrete. When the depth of the neutral axis moves to within 1 inch of the interior surface of the roof, cracks are assumed to penetrate the roof slab.

Due to the difference in roof design, the LAW Vault roof could not be analyzed in the same manner as the intermediate level vaults. The roof slab has only 5 ft of unsupported span between the AASHTO beams. Preliminary calculations indicated that the 16-inch concrete slab can support soil loads across the slab even after significant degradation of the steel. Therefore, collapse of the vault will be determined by the ability of the AASHTO beams to support the structure. A moment arm calculation was used to calculate the moment at midspan of the beams after soil loading. This was then compared to the ultimate momenet[2] of the beams. Because the moment is approximately proportional to the steel area, the ratio of actual moment to ultimate moment is approximately equal to the amount of steel area that can be lost before collapse:

$$A_{crit} = A_{init} * \frac{M_{pred}}{M_u}$$

where:

A_{crit}	=	critical steel area (the minimum area of steel in the AASHTO beams which is capable of supporting the soil load),
A_{init}	=	initial steel area in the AASHTO beams (7.01 inch^2),
M_{pred}	=	predicted moment in beam after soil loading, and
M_u	=	ultimate moment in beam.

In the model, then, collapse occurs when the steel area in the beams is reduced to A_{crit}

[2]The ultimate moment is the maximum moment that the system can support before collapse.

The NAWY models (Nawy, 1989) were used to calculate loss in prestress in the beams due to elasticity loss, creep, shrinkage and relaxation. The model predicted that 90% of the prestress loss occurs in the first 10 years after release, and was in agreement with the prestress loss calculations by Tindall Concrete Georgia, Inc. (hereafter referred to as "Tindall Concrete"). A value of 22 % prestress loss was used as a conservative upper bound in the above calculations.

The LAW Vault walls were analyzed using the same RCPC-based code that was used for the intermediate level vaults. To do so, an equivalent roof slab was formulated for input into the code. After the roof slab of the LAW vault is cast, the system gains redundancy as a continuous, composite beam. The earth load was analyzed with the RCPC model using end span and wall models similar to that used for the intermediate level vaults. An equivalent roof slab width was computed to use a rectangular beam of 70-inch depth (the depth of the composite roof slab/AASHTO beam system) and produce the same moment as the composite slab and beam:

$$b = \frac{886200*12}{70^3} \approx 13 \text{ in},$$

where:

b	=	equivalent slab width;
886200	=	I value of composite slab and beam system (from Tindall, 1993).

In this manner the RCPC-based code can be used to analyze stresses in the LAW vault walls.

4. MODELING APPROACH

4.1 COMPUTER CODES

The RCPC code (Furlong, 1991), as it is commercially available, is an interactive program; all input is typed in as the program runs, and output can be directed to the screen and/or a printer. In order to facilitate multiple model runs during the sensitivity analysis, and to maintain adequate Quality Assurance, the model was first modified to a file-based input/output system. In addition, minor modifications were added to compute stresses in rebar.

The NAWY models (Nawy, 1989) were used to evaluate prestress loss in the AASHTO beams and to confirm various calculations performed by Tindall Concrete. In addition to calculating time-dependent prestress loss, the NAWY models capabilities include service load analysis, strength analysis and design in flexure, shear reinforcement selection, and time dependent deflection of prestressed concrete beams.

4.2 LINKING BETWEEN DEGRADATION AND STRUCTURAL MODELS

The degradation model and structural model (modified RCPC) were combined, and a time loop was added so that the state of the structure through time could be modeled. The time loop was implemented as follows: First, the structural model is run at time zero on (undegraded) structure. Next, the degradation model is run to determine the impact of degradation mechanisms on the physical state (thickness of concrete, diameter of reinforcing rebar, etc.) of the structure using a user-specified time step. After the degradation model is run, a temporary file is created that contains the modified concrete and reinforcing steel specifications. This file is then used as input for the next run of the structural model. Following the structural model run, the degradation model is run again, and the temporary file is updated. This process of alternating between the structural and degradation models continues until the user-specified end of the simulation (e.g., 1,000 years). The state of the structure is printed at a user-specified time interval (e.g., 50 years).

4.3 HYDRAULIC CONDUCTIVITY

4.3.1 Vault Roofs

Walton (1993), presents a calculational method for Effective Hydraulic Conductivity (K_{eff}) of the vault roof. This method considers the adjacent porous media overlying the concrete roof. We have applied Walton's method in our K_{eff} determination. The closure design for each of the three vault designs considered in this report places a clay barrier over the roof to divert infiltration away from the roof. The infiltration flows laterally away from the vault through a granular drain layer which directly overlies the clay barrier. Only a very small amount of the infiltration will penetrate the intact clay barrier. During the period of performance in which the concrete contains no cracks or during which the cracks do not fully penetrate the roof, the infiltration which penetrates the clay barrier will drain off of the sloped roof. The limiting barrier to flow will be the reinforced concrete. With cracking of the roof under applied stresses, the clay barrier will limit the infiltration to the roof, and any infiltration passing through the clay will likely enter the vault through penetrating cracks. The clay barrier is assumed to stay intact until collapse of the vault structure.

K_{eff} of the clay barrier and the concrete roof of the vault were derived using separate equations. The calculation of K_{eff} assumes steady, saturated flow through a set of equally spaced, parallel fractures in the concrete. The following equations after Walton (1993) derive the K_{eff} of the clay layer in the presence of fully penetrating cracks in the concrete.

$$K_{eff} = \xi \, K_{clay} \text{ , and}$$

$$\xi = \left(\frac{1}{2} + \frac{\tanh\left(a + b \ln\left(\frac{1}{x}\right) + c \ln(z) \right)}{2} \right)^{d}$$

where

K_{clay}	=	hydraulic conductivity of the clay layer (m/s),
ψ	=	1/2 of crack width (m),
x	=	X/ψ = dimensionless crack spacing,
z	=	Z/ψ = dimensionless thickness of the clay layer,
H	=	depth of perched water on top of the vault (m),
X	=	1/2 of the crack spacing (m),
Z	=	thickness of the clay layer (m),
a	=	0.0477, b = 0.606, c = 0.479, and d = 0.845.

The assumption of steady saturated flow through the clay layer can be demonstrated by calculating the depth of perched water above the clay layer in the granular drain. The analytic solutions for these equations are provided by McEnroe (1993). For the EAV geometry and hydraulic conductivity of the clay and granular drainage layer, a perched water table equal to the thickness of the granular drain was calculated, thereby verifying our assumptions.

The calculations of Y.,H assume that the cracks are not infilled with porous material. Infilling of the cracks would result in much lower hydraulic conductivity of the clay/concrete layered system when the cracks have fully penetrated the concrete.

4.3.2 Vault Walls

The model for the hydraulic conductivity of the vault roofs assumes that the soil adjacent to the roof will be saturated. This will generally not be the case for the vault walls. Similar models to estimate the hydraulic conductivity of a cracked vault/unsaturated soil system are not available at this time. Nevertheless, the hydraulic conductivity of the walls will be limited by the conductivity of the adjacent material. Therefore, the unsaturated hydraulic conductivity of the adjacent backfill material can be used as an upper bound for the hydraulic conductivity of the cracked wall/soil system Oust as the saturated hydraulic conductivity of the adjacent clay was the limiting value for the hydraulic conductivity of the cracked roof/soil system). The unsaturated hydraulic conductivity of the backfill material (or any soil) is a function of its moisture content. The Idaho National Engineering Laboratory is in the process of conducting flow and transport modeling for the vaults. They utilized a VanGenuchten approach to generate a moisture characteristic curve for the backfill material. This curve provides the relationship between moisture content and hydraulic conductivity. Model results indicate that the backfill will have a greater moisture content near the top of the vault, and therefore it will have a correspondingly greater hydraulic conductivity. For the intermediate level vaults, the unsaturated hydraulic conductivity of the backfill material adjacent to the walls was estimated as 7.5E-4 cm/s near the top of the walls, 6.7E-4 cm/s at mid-height of the walls, and 6.9E-4 cm/s near the bottom of the walls. For the LAW Vault, the unsaturated hydraulic conductivity was estimated as 7E-4 cm/s near the top of the walls, and 6.3E-4 cm/s at mid-height and at the bottom of the walls. Thus, a value of 7.5E4 cm/s can be taken as a worst-case assumption for the hydraulic conductivity of the vault walls.

4.4 MODEL OUTPUT

Model output can be divided into two broad classes; degradation output and structural output. Structural output for the LAW vault includes additional parameters specific to the calculation of stress and cracking in the roof slab due to curvature over the walls. Output parameters are summarized in Table 1. Output is directed to two files. One file contains a summary of all structural parameters at each print interval. In order to facilitate plotting and interpretation, the second file contains one line per print interval. Rebar stress in the first 4 spans (for example, the first wall and the first three cell roof spans) and all degradation parameters are sent to this file.

4.5 DEFINITION OF FAILURE

Failure of a vault can be defined in three ways:

- Loss of ability to resist penetration from drilling.
- Loss of ability to divert water around the vault.
- Structural failure (collapse) of the vault.

Resistance to drill penetration is necessary to avoid accidental intrusion after the period of institutional control, for example, from a future resident attempting to put in a drinking water well. The geology in the vicinity of the vaults, to depths of approximately 200 ft, is made up of soft sediments only. Therefore, drill equipment is not outfitted for hard rock penetration. In the event that an attempt was made to drill over the vaults, the supervising geologist would almost certainly pull up and move over until a normal amount of resistance was encountered. Even in the event that the vault was highly degraded (for example, without rebar and with the consistency of limestone), the supervising geologist would again probably decide to pull up and move. This information on drilling equipment and procedures was obtained through a phone conversation with an experienced geologist in drilling oversight at the Savannah River Site (Asquith, 1993). Thus, drill penetration of the vaults is not expected to be of concern.

Intact concrete generally has a very low hydraulic conductivity; the E-Area Vaults concrete has a hydraulic conductivity of at most 10^{-12} m/s. Therefore, virtually all of the conductivity of the degraded structure will be through fractures. Calculations by INTERA indicate that, once fractures have penetrated the roof slab, the hydraulic conductivity will be very close to that of the clay overlying the vaults, or 10^{-9} m/s. Thus, loss of ability to divert water coincides with crack penetration of the roof.

The modeling approach to collapse of the vaults has been described previously. When a vault roof collapses, the engineered soil cap will also be compromised due to subsidence of the vault roof. This, in turn, will result in a very dramatic increase in hydraulic conductivity of the vault/soil cap system.

4.6 SUMMARY OF CONSERVATIVISM

This section summarizes the conservative assumptions made and approaches taken during the development and application of the performance assessment model. One of the assumptions having the greatest impact on model results was that the concrete was at a relatively low pH (at most 9.5). This results in more rapid degradation of the structure (basically due to more rapid rebar corrosion rates), and causes the estimated service life (i.e., time to crack penetration and collapse) to be several hundred years less than that of high-pH concrete. The sulfate attack rate is based upon empirical experiments using blocks of concrete. The equation was based on the observed attack rate at the location of greatest corrosion (at the corners of the blocks). Rebar corrosion will generally proceed via either anoxic or oxic corrosion. However, because it is not known at this time which mechanism will dominate at any given time, the rates were summed to estimate the rebar corrosion rate. This is clearly conservative because the sum will be greater than either rate individually. The soil cover was assumed to be of constant depth throughout the simulation. In reality, some erosion will take place in the 1,000 to 3,000-year period simulated, resulting in less load on the vaults and therefore lower stress levels and longer service life. In the structural model, a 1-way analysis was used. This examines the stress in a beam supported at each end (Figure 4). Because the roof is supported by four walls, a cross-section receives some support from adjacent walls as well as the walls at each end. Thus, estimated stress levels will be slightly (approximately 3 %) higher than those estimated by a 2-way analysis. The structural analysis also assumed that there would be no interior support provided by the contents. Clearly, if the contents provided some support, there would be less deflection and therefore less stress in the concrete members. In examining the prestressed bridge beams in the LAW vault, a 22 % loss in prestressing was assumed. This was estimated to be a maximum loss of prestress. Actual losses can be expected to be less, particularly in the first 5-10 years after release. Cracks were assumed to penetrate the ILNT and ELT vault roofs mid walls, and the LAW walls, when stress in rebar reached 40 ksi. This was estimated to be a conservative estimation of when crack depth would be sufficient to penetration the concrete members. For the LAW vault roof, crack depth was based upon a calculation of the depth of the neutral axis. To add conservatism to the estimation, cracks were assumed to penetrate when the depth of the neutral axis reached within I inch of the bottom of the roof slab. The approach for estimating the hydraulic conductivity of the cracked concrete assumed that cracks were evenly spaced across the entire surface of the concrete. In reality, the concrete can be expected to crack in fairly localized regions. This is particularly evident in the LAW vault roof, which is expected to crack only within a less than 2-foot wide region over the walls. This assumption is not expected to have a large impact on the calculated hydraulic conductivity, however, because a few cracks are sufficient to cause large changes in hydraulic conductivity. In contrast to the model assumptions, most of the input parameters for the baseline case utilized on average or typical values. For example, all chemical concentrations in groundwater were based on average values, reaction rates were based on the midpoint of the range of values found in the literature, and roof thickness and wall height used were the average (where variation existed).

5. INPUT SUMMARY

Model input for the structural analyses are listed in Tables 2 - Table 4 for the three vault types. Structural input essentially consisted of the dimensions of the vaults (wall height and thickness, roof span and thickness), the size and spacing of the rebar, the depth of cover over the rebar, the compressive strength of the concrete, and the yield strength of the rebar. The required information was obtained from the design drawings for the E-Area Vaults. A list of the drawings used is provided in Table 5.

Input required by the degradation portion of the model is listed in Table 6. Where available and applicable, ranges of values for the input parameters are presented. Input requirements include concentrations of corrosive components of the adjacent groundwater, concentrations of components in the concrete, and reaction rates.

A baseline run was defined to determine a best estimate of the times to crack penetration and failure of the three vault designs. In the baseline case, average values of environmental parameters were used (for example, sulfate concentration of the groundwater). Actual or proposed design parameters (such as rebar size or depth of soil cover) were used. Where design parameters were variable (such as roof thickness in the intermediate level vaults), average values were used.

Soil loading in the baseline case assumed a 9-foot depth of soil cover. A value of 1.7 g/cm^3 (106 lb/ft^3) was used for the density of soil. In order to calculate the self-weight of the vault roofs, a concrete density of 2.34 g/cm^3 (146 lb/ft^3) was used. Lateral soil pressure on the walls was computed using a modified Rankine approach (Das, 1985).

6. MODEL RESULTS

Figure 6 is a cross-section of the ILNT Vault after 400 years of simulated degradation. The sulfate attack mechanism has removed an average of 0.19 cm from the surface of the concrete, and the rebar radius has been reduced from 1.25 cm to 1.05 cm, from a #8 bar to a radius somewhat less than that of a #7 bar. Figures 7 through 9 present the effective hydraulic conductivity of the three vault designs. Prior to crack penetration, the hydraulic conductivity remains that of intact concrete, 10^{-12} m/s. When cracks penetrate the roof of the vault, the hydraulic conductivity of the (cracked) concrete increases to a conductivity near that of the surrounding clay, 10^{-9} m/s increase, up to a theoretical maximum of 10^{-9} m/s.

Table 7 and Table 8 present summaries of the rebar stress for the baseline cases of the ILT and ILNT vaults, respectively. Each column in the tables represents a particular location in the vault. In this summary presentation, rebar stresses are tabulated at each time step for which an "event" occurs, with an event defined as crack penetration at some location in the vault, or collapse of a cell. Shading in the tables indicates that cracks have penetrated at that location. A box created with thick table lines indicates the time of roof collapse for each cell.

The ILT scenario is fairly straight-forward. Maximum rebar stress occurs at mid-span in the roof, due to the fact that there is twice as much rebar in the region over the walls as there is at mid-span. Rebar stress is slightly less over the interior wall than at midspan. Thus, crack penetration occurs first at mid-span in the roof (year 790) , and soon thereafter over the interior wall (year 850). Rebar stress in the walls is much less than that in the roof, primarily because the lateral soil pressure on the walls is much less than the vertical soil pressure on the roof (lateral pressure is approximately one-third that of vertical). Thus, cracks do not penetrate the center region of the wall, or mid-height of the wall, until year 1,080. The rebar stress level in the roof rebar at mid-span and over the interior wall reaches its yield strength in years 1,125 and 1,150, respectively (not shown). As moment is transferred to the remaining rebar stress point at the exterior wall, this causes a rapid increase in rebar stress levels at this point, and cracks penetrate the roof over the exterior wall at year 1,225. The rapid increase in roof rebar stress over the exterior wall continues, and collapse of the roof occurs in year 1,300. With the loss of support from the roof, it is reasonable to assume that, although rebar stress in the walls near the roof and floor have not reached the levels indicative of crack penetration, the walls at this point will also fail and collapse.

Stress patterns in the ILNT Vault are similar to those in the ILT Vault, in that the rebar stress in the roof span of the exterior cells (cells 1 and 7 of Figure 1) over the exterior wall is much less than that over the interior wall of the same cell. In the first interior cell (cells 2 and 6), this effect is mediated somewhat, and in the remaining cells the rebar stress levels are equal over each wall for a given cell. The lower stress level over the exterior wall results in higher rebar stress levels at mid-span of the exterior cell. Thus, crack penetration occurs first at mid-span of the exterior cell (year 570), followed by the first interior wall (year 675). Next cracks penetrate over the remaining walls (year 750), followed soon thereafter by crack penetration at mid-span of the remaining cells (year 775). Cracks do not penetrate the roof over the exterior walls until year 1,000. The first cells to collapse are the first interior cells (cells 2 and 6), in year 1,045, followed soon by the remaining interior cells in year 1,075. The exterior cells collapse in year 1, 125. In the ILNT vault, the walls are slightly higher than the ILT vault, so the stress levels are correspondingly greater, with the result that cracks penetrate at mid-height in year 800, and near the top of the vault in year 1,050. Stress levels at the bottom of the walls have not reached the levels indicative of crack penetration at the point at which the roof has collapsed in all cells (year 1, 125).

Due to the different design and consequent different approach to the analysis, the same type of table cannot be generated to summarize the LAW vault progression through failure and collapse. While crack penetration in the walls is indicated in the same manner (i.e., rebar stress above 40 ksi) as in the intermediate level vaults, crack penetration in the roof is indicated by depth of the neutral axis. Collapse is indicated by the area of prestressed steel in the AASHTO beams dropping below a critical level. The scenario can be described as follows: Cracks penetrate the roof due to curvature over the walls in year 1,420. Next, cracks penetrate at the top, mid-height, and bottom of the walls in years 2,015, 2,235 and 2,300, respectively. Finally, prestress steel loss is sufficient to cause collapse of the roof in year 3,110.

7. SENSITIVITY ANALYSIS

There are three classes of model input that could be considered in the sensitivity analysis. First, sensitivity analysis could be conducted for physical parameters, such as water chemistry or infiltration rates, which are represented by mean values, and are used in the models for the degradation of concrete. Second, sensitivity analysis could be performed for concrete degradation model parameters, such as reaction rates for any of the various degradation reactions. Finally, sensitivity analysis could be conducted on design parameters, such as depth of soil cover, thickness of roof slab, or diameter of rebar. All sensitivity analyses were conducted by varying a single parameter from the baseline case and leaving all other parameters unchanged. This section presents the rationale behind the selection of parameters to be included in the sensitivity analysis, and the results of the analysis.

7.1 SELECTION OF PARAMETERS AND VALUES

Calcium hydroxide is one of the primary buffers that contribute to the high pH of concrete. Based on an X-ray diffraction analysis of a sample of the E-Area Vault concrete, the concrete used for the E-Area Vaults contains no calcium hydroxide. This can be explained by a combination of two factors. First, the cement used in the concrete has a very low calcium hydroxide content. Second, the concrete is designed so that the calcium hydroxide will be removed via a reaction with slag in the concrete. Calculations by Chris Langton of the Savannah River Technology Center determined that the pH of the E-Area Vault concrete is approximately 8, that it is at most around 9 to 9.5, and that it may be as low as 7. Because the E-Area Vault concrete has essentially no calcium hydroxide content and a relatively low pH, the only degradation mechanisms that apply to the concrete are oxic and anoxic ("hydrogen evolution") corrosion of rebar, and sulfate attack. While varying the parameters relevant to the sulfate attack mechanism caused noticeable changes in the amount of surface loss due to sulfate attack, the impact on steel stress was minimal. The oxic corrosion rate has a slightly greater impact on steel stress, but the anoxic corrosion rate by far dominates the rebar corrosion. Thus, for low-pH concrete in the Savannah River Site environment , the only degradation process of interest in terms of the sensitivity analysis is hydrogen evolution corrosion of rebar. This process is modeled using only one parameter, the hydrogen evolution corrosion rate. Therefore, this parameter was selected for inclusion in the uncertainty analysis. Based on a literature review, the low-pH hydrogen evolution corrosion rate was varied between 1E-3 and 1E-4 cm/yr, and the high-pH of hydrogen evolution corrosion between 1.5E-4 and 1E-5 cm/yr. It is important to note that the low-pH assumption is generally conservative, in that most degradation mechanisms proceed at higher rates in the low-pH environment. The only exception is that, with calcium hydroxide leaching, there can be some decrease in concrete strength. Since the E-Area Vault concrete has no calcium hydroxide available for leaching, the concrete strength is assumed to remain constant throughout the simulation.

A preliminary sensitivity analysis was performed to help determine parameters for which to conduct a detailed sensitivity analysis. Of the parameters included in the initial sensitivity analysis, hydrogen evolution corrosion rate (discussed above) and depth of concrete cover over rebar was selected for detailed analysis. Design constraints limited the range of allowable cover to between 1 ½ and 3 inch. In addition, thickness of vault roofs and numerous parameters related to degradation mechanisms were considered in the initial sensitivity analysis, but not selected for detailed analysis.

New parameters selected for detailed analysis were rebar diameter, size of AASHTO beams (LAW Vault only), concrete strength, and depth of soil cover over the vaults. Rebar diameter was varied approximately to the minimum and maximum allowable according to ACI 318. The limits varied between vaults and between walls and roofs depending on the values of the relevant design parameters. Standard AASHTO beam sizes were used in the sensitivity analysis. Because changing the size by only one increment is very significant both in cost and in strength of beam, only types III, IV, and V beams were analyzed for the sensitivity analysis. Finally, a minimum soil cover of 8 ft is required to meet performance requirements. This was varied up to a maximum of 16 ft. For all parameters, intermediate values (i.e., between the extremes and the baseline) were selected as appropriate.

7.2 OUTPUT SUMMARY

In the sensitivity analysis, the first time of crack penetration of the roof and wall of the intermediate level vaults are reported, and, for the ILNT vault, the first cell to collapse. The first crack penetration occurs at mid-span of the exterior cell. (for the ILT vault, the two cells are equivalent). The first cells to collapse in the ILNT vault are the first interior cells towards each end (cells 2 and 6). Collapse in a cell is indicated when the rebar reaches yield strength at mid-span and over the adjacent walls of that cell. In cells 2 and 6, the first location at which the rebar reaches yield is at mid-span, followed by the wall towards the exterior end of the vault. Collapse, then, occurs when the rebar in the roof reaches yield strength at the remaining location, over the wall towards the interior of the vault. Thus, for the sensitivity analysis of the ILNT Vault, this is the location of interest. By observing the stress in the roof rebar at this location, the time to collapse can be determined. Similarly, for the ILT vault, the last location in the cells to reach yield strength in the rebar is over the exterior wall. Finally, crack penetration of the walls at mid-height was used to indicate crack penetration of walls.

For the LAW Vault, collapse is indicated by prestress steel in the AASHTO beams reaching a critical level. Therefore, observing changes in the area of prestress steel will provide the determination of time to collapse. Crack penetration of the roof is indicated by the neutral axis approaching to within 1 inch of the bottom of the roof slab. As in the case of the intermediate-level vaults, crack penetration at mid-height of the walls was selected to indicate crack penetration of the walls.

Thus, for each vault, three critical output parameters have been selected on which to base the sensitivity analysis of the six input parameters. The output parameters can be used to determine the time to crack penetration of the roof, time to crack penetration of the walls, and collapse of the vaults. These pivotal times are summarized for the baseline case in Table 9.

Table 10 through Table 12 summarize the same pivotal times for each sensitivity run. For the LAW Vault, differences existed in some of the parameters between the different vault components, and these differences are indicated in the left-hand column of Table 12. For example, the AASHTO beams are made of a high-pH concrete. Therefore, they will be subject to the slower, high-pH rate of hydrogen evolution rebar corrosion. Furthermore, since they are on the interior of the vault, there are no corrosive processes available to lower the pH of the beam concrete and thereby increase the reaction rate. In addition, the rebar used in the roof and walls are different. In order to understand the dynamics of the vaults in greater detail, plots of steel stress vs. time are also presented for most of the sensitivity runs.

7.2.1 ILNT Vault Sensitivity Analysis

Pivotal times (time to crack penetration of the roof, time to crack penetration of the walls, and time to collapse) for the ILNT vault are summarized in Table 10.

All pivotal times are sensitive to hydrogen evolution corrosion rate (Figures 10, 11 and 12). Varying the corrosion rate over a range of one order of magnitude changed the pivotal times by an order of magnitude as well. The change in pivotal times is very close to proportional to the ratio of the baseline corrosion rate divided by the new corrosion rate. Increasing the corrosion rate from 5E-4 to 1E-3 changed the time to crack penetration (of the roof) from 570 years to 285 years, a decrease of 285 years, and decreasing the corrosion rate to 1E-4 increased the time to crack penetration to 2,775 years, an increase of over 280%. Decreasing the corrosion rate to only 2.5E-4 almost doubled the time to crack penetration of the roof.

Altering the depth of the soil has less impact on the pivotal times (Figures 13, 14 and 15). Decreasing the soil cover from 9 ft to 8 ft increases the pivotal times by approximately 50 to 100 years. Increasing the soil cover to 12 ft decreases the pivotal times by approximately 200 years, and increasing to 16 ft decreases the pivotal times by 300 to 400 years from the baseline values.

Changing the rebar size has the potential to create large changes in the pivotal times. Reducing the bar size to #6 would result in cracks penetrating the roof immediately upon soil loading (Figure 16), and the wall after 175 years (Figure 17); collapse would occur in 425 years (Figure 18). Using a #7 instead of the present #8 would result in crack penetration of the roof after 250 years, and collapse after 735 years. Increasing the rebar size has similarly dramatic effects. Using #9 rebar would increase the pivotal times to on the order of 1,000 years, and #11 to on the order of 2,000 years.

Depth of concrete cover over the rebar has little impact on the longevity of low-pH vaults (Figures 19, 20 and 21). Note that this statement applies to the range of 1 ½ - to 3-inch depth of concrete cover. Further decreasing the depth of cover further could have significant effects. Also, concrete cover over rebar can have very significant impacts if high-pH concrete is used; with increased cover reducing corrosion and thus extending the service life of the vault. Stress is slightly higher with greater depth of cover, and remains so throughout the simulation. Analysis of high-pH concrete (not shown) by INTERA demonstrated that depth of concrete cover over rebar can be very important. In high-pH concrete, several diffusion-limited processes become important. The result is that rebar with greater depth of cover degrades at significantly slower rates, and therefore, in the long term, experiences lower stress levels.

Concrete strength also has little impact on the longevity of the vault (Figures 22, 23, and 24). The reason for this is that concrete has very low tensile strength, and the rebar therefore provides the majority of the tensile strength in reinforced concrete. Thus, increasing the concrete strength decreases the stress levels in the rebar only slightly. High strength concrete provides other advantages, however, such as resistance to shear stress and reduced hydraulic conductivity.

7.2.2 ILT Vault Sensitivity Analysis

Pivotal times for the ILT Vault are summarized in Table 11. The results are qualitatively very similar to those of the = vault, with quantitative differences caused by the slight differences in some of the design parameters. Again, changes in pivotal times are roughly proportional to changes in hydrogen evolution corrosion rates. At the lowest rate, cracks did not penetrate the ILT Vault prior to the end of the 3,000-year simulation (Figures 25, 26 and 27). At the minimum depth of soil cover, pivotal times decreased by approximately 50 years, and at the maximum, decreased by 300 to 400 years (Figures 28, 29 and 30). Due to the thicker roof in the ILT Vault, #6 rebar did not result in crack penetration of the roof until year 155 (Figure 3 1). Otherwise (Figures 32 and 33), changing rebar size had similarly dramatic effects on the ILT Vault as was the case with the ILNT vault. Due to the overall more conservative design of the ILT Vault, depth of concrete cover over rebar (Figures 34, 35 and 36) and concrete strength (Figures 37, 38 and 39) had even less impact on the ILT vault than on the ILNT vault.

7.2.3 LAW Vault Sensitivity Analysis

Pivotal times for the LAW Vault sensitivity analysis are summarized in Table 12. Figure 40 shows the location of the neutral axis as a function of time for various rates of hydrogen evolution rebar corrosion. The depth is given in terms of the distance from the interior surface of the slab. This is done for two reasons. First, at the same time that the neutral axis is moving to lower positions in the slab, sulfate attack is removing surface material from the top of the slab. Therefore, indicating the depth of the neutral axis as a distance from the exterior could be misleading, and, at best, confusing. Second, cracks are assumed to penetrate the roof slab when the depth of the neutral axis reaches I inch. Thus, displaying the depth of the neutral axis in this manner provides a graphical interpretation of the time to crack penetration. In spite of the differences in design between the LAW and intermediate level vaults, and the resultant differences in the structural calculations, the changes in the time to crack penetration of the roof remain roughly proportional to the changes in the corrosion rate. Crack penetration of the LAW walls also maintains this proportionality (Figure 41).

Figure 42 shows the results of the sensitivity of time to roof collapse of the LAW vault for both hydrogen evolution corrosion rate and depth of soil. The curves represent the area of prestressed steel remaining for different hydrogen evolution corrosion rates, as a function of time. The horizontal lines indicate the area of prestressed steel required to support different depths of soil. The intersection of a curve with a line, then indicates the point in time at which collapse will occur for a given combination of corrosion rate and soil depth. To interpret the impact of hydrogen evolution corrosion rate, consider the horizontal line corresponding to the baseline soil depth (9 ft), and disregard the other horizontal lines. This line indicates the rebar area necessary to support the weight of the vault and 9 ft of soil. When a particular curve crosses that line, that point in time is the time of collapse for that hydrogen evolution rate and the baseline (9 ft) depth of soil. These are the times that are presented under "Hydrogen Evolution Corrosion Rate" in Table 12. The proportionalities are maintained here as well, but not quite as close as in the other cases. At the highest corrosion rate, collapse is predicted at 1,600 years, and, at the lowest rate, the vault did not collapse prior to the end of the 10,000-year simulation.

Because crack penetration of the roof is based upon a neutral axis calculation, and the depth of the neutral axis is not calculated as a function of loading, soil loading does not change the time to crack penetration of the roof. In reality, because increased soil loads will increase the stress level in the rebar, changing soil depth would be expected to have a small impact on the depth of cracks, and therefore on the time to crack penetration. It may appear from the graph of wall stress for different soil depths (Figure 43) that soil load has less impact on LAW walls than on the walls of the intermediate-level vaults. The absolute change, however, remains close to that of the intermediate level vaults: pivotal times are approximately 100 years greater than baseline times for the minimum depth of soil, and 200 to 300 years less for the maximum depth of soil. To examine the impact of soil depth on collapse of the vault, return to Figure 42. This time, consider the baseline hydrogen evolution rate (8E-5) curve only, and neglect the other curves. When the baseline curve crosses the horizontal line for a particular soil depth, that indicates the time to collapse for that depth of soil. These are the values tabulated in Table 12 under "Depth of Soil Cover" (of course, other corrosion rate/soil depth combinations can also be interpreted from this graph). Depth of soil has a much more dramatic impact on time to LAW Vault collapse than on any other pivotal time (for the LAW Vault and the intermediate level vaults). At the minimum depth of soil, roof collapse increases by almost 200 years, and at the maximum, decreases by over 1,000 years.

Figure 44 shows the impact of changing rebar size on the time to crack penetration of the roof, using the same format as Figure 40. Because the rebar in the roof slab is close to the ACI minimum, only one increment smaller (from #6 to #5) was used in the sensitivity analysis. Again, the effects are significant, decreasing the time to crack penetration by approximately 300 years. Nevertheless, this is still several hundred years greater than the time to crack penetration of the roof in the intermediate level vaults. Increasing the rebar size also has a significant impact on the time to crack penetration of the roof. Increasing to 1 #8 bar increases the time to crack penetration by 600 years, and, to #14, by approximately 2,400 years. Note that, in this case, the roof win collapse due to structural failure of the AASHTO beams before cracks penetrate the roof. Changes in crack penetration of the walls (Figure 45) are similarly dramatic, with a change of approximately 300 years for every unit increment in bar size. Because roof collapse is determined by the AASHTO beams, changing the bar size in the roof slab has no impact on time to collapse.

Increasing the size of the AASHTO beams from the current Type IV to Type V will have a relatively slight impact on the depth of cracks and therefore on the time to crack penetration. This is due to the neutral axis' lack of dependence on load factors and on the moment in the AASHTO beams. Due to the decreased stress levels in the roof slab rebar (not shown), some decrease in the time to crack penetration would be expected. Decreasing to Type III beams will result in increased stress levels in the roof slab rebar, caused by increased curvature over the walls. Stress levels will be sufficient to cause cracks to penetrate the roof slab (that is, greater than 40 ksi) immediately upon soil loading. Therefore, use of smaller beams is not recommended unless spacing between beams is decreased to compensate. Figure 46 illustrates the impact of using different sized AASHTO beams on the time to collapse, using the same format as Figure 42. The curves for various hydrogen evolution corrosion rates have been retained in order to maximize the amount of information available in the graph. In Figure 46, however, the horizontal lines represent the area of prestress steel required to maintain the structure for the different sizes of AASHTO beams. Using a larger beam results in a smaller requirement in terms of the area of prestress steel required. Using the baseline hydrogen evolution corrosion rate, changing the beam size changes the time to collapse by approximately 300 to 400 years.

7.3 SUMMARY OF THE IMPACT OF DESIGN CHANGES

Within the range of values selected (3,000 to 6,000 psi), concrete strength has little impact on the service life of the vaults, due to the fact that it is predominately the rebar that resists tensile stresses. It is important to note that concrete strength has other important contributions to the vaults, such as reducing permeability and resisting shear stress. Depth of concrete cover over rebar also had little impact on the service life of the vaults. There are two significant caveats to this statement, however. First, this statement applies to the range of 1 ½ - to 3-inch depth of concrete cover. Further decreasing the depth of cover further could have significant effects. Second, concrete cover over rebar can have very significant impacts if high-pH concrete is used, with increased cover reducing corrosion and thus extending the service life of the vault.

Rebar size has notable impacts on the service life of the vaults. Increasing or decreasing the rebar by one increment (for example, from #8 to #9 or #7) will increase or decrease, respectively, the service life of the vaults by from 200 to 300 years. Further increments in rebar size have similar effects. This is due to the increased cross-sectional area of the rebar. Thus, increasing or decreasing the rebar spacing would be expected to have impacts of the same type and magnitude.

The size of the AASHTO bridge beams that are used for the roof system in the LAW vaults has a significant influence on serviceability. In addition to the Type IV beams now used, smaller Type III and larger Type V beams were considered for this study. It was assumed that the spacing, amount of prestress steel, and amount of prestress applied were the same for each beam type. The nominal stiffness of beams is reflected by the I value. The ratio between Type III and Type IV beams is 125,390/260,741 = 0.48. After the 16-inch slab is cast for composite action with the girders, the relative stiffness ratios will be higher, perhaps 0.6 to 0.7. The curvature of the slab over supports will be 30 to 40% larger as the smaller girders rotate at supports more than the Type IV girders when soil is placed over the hardened slabs. Consequent cracking will result in larger and deeper cracks over supports, and probable crack penetration upon soil loading. The limit strength at midspan will be proportional to the overall depth from the top surface of the slab to the centroid of prestressed strands at midspan. As a consequence, roof collapse is predicted to occur approximately 400 years earlier if the smaller beams are used. The ratio between the nominal stiffness of Type V and Type IV beams is 521,100/260,741 = 2.0. After the 16-inch roof slab is added, the stiffness ratio will become 1.6 to 1.8. With greater stiffness, the deeper girders will rotate at supports through smaller angles than will Type IV beams, and the curvature in the slabs will be smaller for slabs supported on deeper girders. Cracking from such smaller curvatures will be smaller and less deep than those for the slabs supported on Type IV beams, although the neutral axis calculation indicates the same depth of cracking. The time to collapse is extended by slightly over 300 years using the larger girders. In summary, the use of the smaller Type III beams is not recommended. Although some of the increased curvature could be compensated for by closer spacing of the beams, it is not likely that this will be practical, as the beam spacing is already relatively small. On the other hand, increasing the beam size will likely have only a slight impact on the time to crack penetration, and a relatively small impact on the time to collapse (increased from 3,110 years to 3,430 years, or by about 10%). Thus, the present beam size seems to be appropriate. It may be possible to alter the beam spacing, however, and retain adequate service life. Larger beam spacing would result in greater curvature and thus decrease the time to crack penetration; and, of course, decrease the time to collapse. In addition, consideration would need to be given to whether the 16-inch roof span could support the larger distance between girders, particularly as the structure degrades. Nevertheless, it seems likely that beam spacing could be altered and the vaults still satisfy the performance criteria.

Finally, depth of soil cover has significant impacts on the service life of the vaults. Decreasing the soil cover from the assumed 9 ft to the minimum of 8 ft increased the service life of the vaults by 50 to 100 years. Increasing the soil cover to the maximum considered, 16 ft, decreased the service life by approximately 200 to 400 years. The notable exception to this is the time to collapse of the LAW Vault, which decreased by over 1,000 years when the soil cover was increased.

8. FUTURE RESEARCH AREAS

This study was limited to the roof and walls of the ILT, ILNT and LAW vault types. If cracks penetrate the roof or walls of a vault before cracks penetrate the floor, there is the potential for infiltration water to enter and accumulate in the vault, resulting in leaching of the vault contents. When the floor does crack, toxic substances could then be released. Clearly, in order to accurately assess flow out of the vaults, it is necessary to estimate the time to crack penetration of the vault floors. This should be the first priority for additional work in this area.

This project has demonstrated the ability of the model to evaluate the impact of changes in design parameters on the longevity of reinforced concrete structures. A number of other design parameters were not considered in this study due to time and budget limitations. Additional sensitivity analyses could be conducted for structural parameters such as roof thickness, rebar spacing, AASHTO beam spacing, length, width and height of the vaults, and wall thickness, as well as degradation model inputs such as oxygen diffusion rate in the concrete, leach rate, carbonation rate, or time to depassivation of the rebar.

One issue that has not been addressed in this project is the potential for loss of bonding between the concrete and rebar as the rebar degrades. Corrosion products have greater volume than the rebar, and this can result in cracking or spalling of the concrete, or other mechanisms may result in loss of bonding.

If high-pH concrete is to be considered, sensitivity analysis should be conducted for other corrosion processes as well. Figures 47 and 48 demonstrate the importance of other processes in the corrosion of high-pH concrete. Figure 47 shows a worst-case degradation scenario at 50 years after burial. Sulfate attack has caused some surface loss. Oxic corrosion has caused the exterior face rebar to corrode at a slightly greater rate than the interior face rebar, which will. remain passivated (and thus not subject to oxic corrosion) throughout the simulation. Leaching has resulted in a low-pH zone to a depth of 5.9 cm into the concrete. At 400 years (Figure 48), the low-pH zone has encompassed the exterior face rebar. This causes the hydrogen evolution corrosion reaction to proceed at an accelerated rate, resulting in significant corrosion of the exterior face rebar. The interior face rebar, still protected from oxic corrosion, corrodes much more slowly, at the high-pH rate of hydrogen evolution corrosion. In a low-pH concrete, both exterior and interior rebar corrode at the higher hydrogen evolution corrosion rate. Thus, the high-pH concrete has two basic differences in terms of its corrosion rates: First, there is a delay, both before the onset of oxic corrosion (minor impact) and before the high rate of hydrogen evolution corrosion (major impact). Second, the interior rebar corrodes only at the lower rate of hydrogen evolution corrosion throughout the simulation (major impact). Because of this, carbonation (which, in some scenarios, may be the mechanism for lowering pH), leach penetration, and time to depassivation of the rebar all become important. Table 13 presents the results of a baseline analysis of baseline results for the different vault types, under the assumption that high-pH concrete is used. This can be compared to Table 9. LAW Vault results for high-pH concrete are not presented because changes were made to the LAW approach such that the initial high-pH results are not directly comparable with the final low-pH results. With high-pH concrete, the time to crack penetration of the roof increases by approximately 600 years for both intermediate level vaults, and the time to collapse increases by approximately 800 years.

An issue that was beyond the scope of this project was the performance of the clay layer overlying the vault. It may be worthwhile to investigate whether cracks in the concrete can result in cracks in the clay. This would increase the hydraulic conductivity of the clay layer and therefore of the clay/roof system. Furthermore, the clay layer is assumed to maintain the same thickness and size over the long time frames of the simulation. The accuracy of this should be investigated, as well as the impact of changes in the clay layer on the performance of the vaults.

Other issues not addressed in this project include the long-term performance of waterstops and control joints, of waterproof coatings placed on the exterior of the vaults, and the longevity of the sealed shrinkage cracks.

Finally, the hydrogen evolution corrosion rate is a significant source of uncertainty in the model. Any work that could determine this rate with greater accuracy would decrease the uncertainty in the model predictions.

9. SUMMARY AND CONCLUSIONS

This study has demonstrated a capability to estimate the degradation of the E-Area Vault structures and to utilize information on the degraded vaults to predict the times to failure (loss of ability to divert water) and collapse of the structures. The primary source of uncertainty in the model is the rate of rebar corrosion due to the anoxic hydrogen evolution reaction, which results in uncertainty of approximately one order of magnitude.

Degradation processes considered were magnesium and sulfate attack, calcium leaching, carbonation, and rebar corrosion due to both oxygen diffusion to the rebar (including breakdown of the passivating layer that initially prevents corrosion of rebar) and due to the "hydrogen evolution" reaction. Existing empirical models for the individual degradation processes were combined into a single model to create an overall model of the degradation of reinforced concrete. The degradation processes were used to predict the condition of the concrete, including its strength, thickness and hydraulic conductivity. The evaluation of structural response to loads and other influences (e.g., slow and steady degradation of reinforced concrete) is made on the basis of the equilibrium of forces and compatibility of deformation within the structure and in the surrounding media using the RCPC computer code as a foundation. In addition, the NAWY models were used to calculate loss in prestress in the beams due to elasticity loss, creep, shrinkage and relaxation. The state of stress in the concrete was calculated and the roof components and walls fractured in order to eliminate excessive stress which cannot be borne by the degraded structure. Crack width and spacing were also computed. By combining the degradation and structural models into a single performance assessment tool, sensitivity analysis can be conducted to determine the impact both of variation in important degradation processes and of changes in design parameters on the service life of the vaults.

Structural data for each vault type was based on a review of design drawings provided to INTERA by WSRC. Relevant environmental data (such as sulfate concentration in groundwater) were obtained through the Idaho National Engineering Laboratory (INEL). Corrosion rates were based upon an extensive literature review. All structural and degradation parameters were reviewed by WSRC and INEL. Structural analysis and calculations were reviewed by an expert structural engineer who specializes in the field of design of reinforced concrete structures.

For each type of vault, sensitivity analysis was performed to bound the predictions. After an initial rough sensitivity analysis on a large number of factors, six factors were selected for detailed sensitivity analysis: rate of rebar corrosion due to the "hydrogen evolution" reaction, rebar diameter, depth of concrete cover over the rebar, size of AASHTO "bridge" beams used to support the vault roof in the LAW vault design, and depth of soil cover over the vaults, and concrete strength. Output parameters for the sensitivity analysis were the time to first crack penetration of the vault roof, time to first crack penetration of the vault walls, and time to structural failure (collapse) of the vault roof. Times to crack penetration are important because the hydraulic conductivity increases by approximately 3 orders of magnitude (over that of intact concrete) upon crack penetration.

From the calculations in this study, we have concluded:

That concrete strength, and, for the low-pH concrete being used in the E-Area vaults, depth of concrete cover over the rebar, have little impact on the vault performance. Depth of soil cover can alter the service life of the vaults on the order of hundreds of years, and rebar size can alter the service life of the vaults on the order of hundreds to thousands of years. Changing the size of the AASHTO beams in the LAW Vaults will change the time to collapse of the vaults on the order of several hundred years. Using a smaller beam, however, is not recommended (unless beam spacing is decreased appropriately), as stress levels in the roof-slab-rebar over the walls will result in crack penetration of the roof upon soil loading.

Future work should include a similar analysis of cracking of the vault floors; in order to accurately assess flow out of the vaults, it is necessary to estimate the time to crack penetration of the vault floors. Sensitivity analyses beyond those conducted for this study could be conducted for structural parameters such as roof thickness, rebar spacing, AASHTO beam spacing, length, width and height of the vaults, and wall thickness, as well as degradation model inputs such as oxygen diffusion rate in the concrete, leach rate, carbonation rate, or time to depassivation of the rebar. In addition, if high-pH concrete is used, additional sensitivity analysis should be conducted on degradation mechanisms important in high-pH concrete. Mechanisms that may result in loss of bonding between rebar and concrete should be investigated and quantified. In addition, performance of the clay layer overlying the vault, of waterstops and control joints, of waterproof coatings placed on the exterior of the vaults, and the longevity of the sealed shrinkage cracks all could warrant further study. Finally, any work that could determine the anoxic (hydrogen evolution) corrosion rate in rebar with greater accuracy would decrease the uncertainty in the model predictions.

This project has demonstrated the ability of the code to estimate the impact of changes in design parameters on the longevity of reinforced concrete structures. The code therefore has potential for application as a design aid tool for below-ground concrete storage facilities. The current mandate at DOE facilities to move in the direction of below-ground disposal in concrete-engineered structures makes this code a potentially important performance assessment tool.

Table 1. Summary of Output Parameters

Parameter Description	Units
Degradation Parameters	
rebar volume lost due to the oxygen-diffusion limited reaction	%
% of rebar volume lost due to the hydrogen evolution reaction	%
total loss of rebar at the exterior and interior face of the slab	% volume loss remaining diameter (cm)
depth of $S0_4$ penetration	cm
Ca(OH)2 leach penetration via the concrete-controlled assumption	cm
Ca(OH)2 leach penetration via the geology-controlled assumption	cm
total leach Ca(OH)2penetration	cm
depth of carbonation penetration	cm
fracture aperture	mm
fracture spacing	m
effective hydraulic conductivity	m/s
Structural Parameters	
moments at critical stress regions	ft-kip
shear at critical stress regions	kip
concrete stresses at critical stress regions	psi
rebar stress at critical stress regions	ksi
concrete cracking stress	psi
concrete shear limit stress	psi
LAW Vault Curvature Parameters	
curvature over walls	radians/in
depth of neutral axis	inch and cm
stress in rebar due to curvature	ksi

Table 2. Structural Input for the ILNT Vault

Variable	"mean"	range	justification
Spans			
Wall floor to roof center	32.5 ft (1)	32 – 33 ft	Variable roof thickness
roof center to first wall center	27 ft		
inner wall center to center	26.5 ft		
Roof thickness	33 inches	27 – 39 inches	
columns			
outer wall thickness	30 inches		
inner wall thickness	18 inches		
misc			
concrete cover over rebar	2.375 inches	1.5 - 3 inches	2.375 actual on blueprint, 2-3 accepted range; may want to go to 4
exterior face bar area	1.58 in^2		
interior face bar area	.79 in^2		
concrete compressive strength	4750 psi		midpoint of minimum spec (4,000) and minimum test (5,500)
rebar yield strength	60 ksi		
degradation			
maximum spacing (outside, at stress points)	12 inches		
rebar diameter	1 inch = 2.5 cm		

(1) based on 29'8" wall and 2'3" to 3'3" roof thickness

Table 3. Structural Input for the ILT Vault

Variable	baseline	range	justification
Spans			
Wall floor to roof center	30.5 ft (1)	30.25 – 30.75 ft	variable roof thickness
roof center to first wall center	27 ft		
inner wall center to center	n.a.		
Roof thickness	48 inches	42 – 54 inches	
columns			
outer wall thickness	30 inches		
inner wall thickness	18 inches		
misc			
concrete cover over rebar	2.375 inches	1.5 - 3 inches	allowable range
exterior face bar area	1.58 in^2		
interior face bar area	.79 in^2		
concrete compressive strength	4750 psi		midpoint of minimum spec (4,000) and minimum test (5,500)
rebar yield strength	60 ksi		
degradation			
maximum spacing (outside, at stress points)	12 inches		
rebar diameter	1 inch = 2.5 cm		

(1) based on 28'6" wall and 3'6" to 4'6" roof thickness

Table 4. Structural Input for the LAW Vault

Variable	Value	Source
AASHTO I-Beams		
Length of I-beam	52'	Tindall
Top flange width	20"	Tindall
Top flange depth	11"	Tindall
Bottom. flange width	26"	Tindall
Bottom flange depth	8"	Tindall
Total depth	54"	Tindall
Web width	8"	Tindall
Concrete compressive strength at 28 days	6,000 psi	Tindall
Concrete compressive strength at prestress	5,000 psi	Tindall
Eccentricity at midspan	17.13	Tindall
Eccentricity at support	12	Tindall
Ultimate strength of prestress steel	250,000 psi	Tindall
Initial prestress	202,500 psi	Tindall
Yield strength of prestress steel	240,000 psi	Tindall
Young's modulus of prestress steel	28,700,000	Tindall
Area of prestress steel	7.01 $inch^2$	Tindall
Number of tendons	42	Tindall
Thickness of roof panels	3"	Design drawings
Thickness of roof slab	16"	Design drawings
rebar area in roof slab	0.88 in^2/foot	Design drawings
prestress loss	22%	Tindall, confirmed by NAWY10

Table 5. Design Drawings Used

Drawing Number	Revision Number	Title
AA98143C-11-A-TC3		AASHTO BEAMS AND ROOF PANELS (BY TINDALL CONCRETE, INC.)
SE5-6-2003303	2	BURIAL GROUND EXPANSION ILT VAULT JOINTS LOCATIONS & DETAILS (U) CONCRETE
SE5-6-2003304	1	BURIAL GROUND EXPANSION ILT VAULT BASE SLAB PLANS (U) CONCRETE
SE5-6-2003305	0	BURIAL GROUND EXPANSION ILT VAULT WALLS REINFORCING ELEVATIONS CONCRETE
SE5-6-2003306	0	BURIAL GROUND EXPANSION ILT VAULT WALLS SECTIONS & DETAILS CONCRETE
SE5-6-2003307	0	BURIAL GROUND EXPANSION ILT VAULT WALLS & CRANE RUNWAY PLAN AND SEC`TIONS CONCRETE
SE5-6-2003308	2	BURIAL GROUND EXPANSION ILNT VAULT JOINTS LOCATIONS & DETAILS (U) CONCRETE
SE5-6-2003309	0	BURIAL GROUND EXPANSION ILNT VAULT BASE SLAB PLANS CONCRETE
SE5-6-2003310	I	BURIAL GROUND EXPANSION ILNT VAULT WALLS REINFG ELEVATIONS (U) CONCRETE
SE5-6-2003311	1	BURIAL GROUND EXPANSION ILNT VAULT WALLS SECTIONS & DETAILS (U) CONCRETE
SE5-6-2003315	0	BURIAL GROUND EXPANSION ILT VAULT PERMANENT ROOF SLAB PLAN & SECTIONS (FUTURE) CONCRETE

Drawing Number	Revision Number	Title
SE5-6-2003317	0	BURIAL GROUND EXPANSION ILNT VAULT PERMANENT ROOF SLAB PLAN & SECTIONS (FUTURE) CONCRETE
SE5-6-2003318	2	BURIAL GROUND EXPANSION ELT & ILNT VAULTS GENERAL NOTES AND LEGEND (U) CONCRETE
SE5-6-2008800	1	BURIAL GROUND EXPANSION LAW VAULT JOINTS LOCATIONS & DETAILS CONCRETE
SE5-6-2008801	1	BURIAL GROUND EXPANSION LAW VAULT GENERAL NOTES AND LEGEND CONCRETE
SE5-6-2008802	0	BURIAL GROUND EXPANSION LAW VAULT FOUNDATION, SLAB & ROOF FRAMING KEY PLANS CONCRETE
SE5-6-2008803	1	BURIAL GROUND EXPANSION LAW VAULT FOUNDATION & FLOOR SLAB PLAN - MODULE 1 CONCRETE
SE5-6-2008806	0	BURIAL GROUND EXPANSION LAW VAULT ROOF FRAMING & SLAB PLAN - MODULE I CONCRETE
SE5-6-2008809	0	BURIAL GROUND EXPANSION LAW VAULT WALLS ELEVATIONS SHEET I CONCRETE
SE5-6-2008810	1	BURIAL GROUND EXTENSION LAW VAULT WALLS ELEVATIONS SHEET 2 CONCRETE
SE5-6-2008811	0	BURIAL GROUND EXPANSION LAW VAULT WALLS ELEVATIONS SHEET 3 CONCRETE
SE5-6-2008812	1	BURIAL GROUND EXPANSION LAW VAULT WALLS SECTIONS & DETAILS SHEET I CONCRETE

Drawing Number	Revision Number	Title
SE5-6-2008813	1	BURIAL GROUND EXPANSION LAW VAULT WALLS SECTIONS & DETAILS SHEET 2 CONCRETE
SE5-6-2008814	I	BURIAL GROUND EXPANSION LAW VAULT WALLS SECTIONS & DETAILS SHEET 3 (FUTURE) CONCRETE
SE5-6-2008815		BURIAL GROUND EXPANSION LAW VAULT WALLS SECTIONS & DETAILS SHEET 4 CONCRETE
SE5-6-2008816	0	BURIAL GROUND EXPANSION LAW VAULT ROOF FRAMING & SLAB SECTIONS & DETAILS CONCRETE
SE5-6-2008817	0	BURIAL GROUND EXPANSION LAW VAULT PRESTRESSED ROOF BEAMS SECTIONS & DETAILS CONCRETE
W2017824	C	BURIAL GROUND EXPANSION ILT, ILNT & LAW VAULTS CLOSURE CONCEPT SITE PLAN CIVIL
W2017825		BURIAL GROUND EXPANSION ILT & ILNT VAULTS CLOSURE CONCEPT SITE CROSS SECTIONS CIVIL
W2017826	B	BURIAL GROUND EXPANSION LAW VAULTS CLOSURE CONCEPT SITE CROSS SECTIONS CIVIL
W2017827		BURIAL GROUND EXPANSION ILT & ILNT VAULTS CLOSURE CONCEPT PLAN AND SECTIONS CIVIL
W2017828	B	BURIAL GROUND EXPANSION LAW VAULTS CLOSURE CONCEPT PLAN & SECTIONS CIVIL
W2020320	1	BURIAL GROUND EXPANSION ILT VAULT CRUCIBLE SILOS PLAN AND SECTIONS CONCRETE

Drawing Number	Revision Number	Title
W2020372	B	BURIAL GROUND EXPANSION LAW VAULTS CONSTRUCTION STRATEGY SITE CROSS SECTIONS CIVIL
W2020422	1	BURIAL GROUND EXPANSION ILT VAULT CRUCIBLE SILOS DETAILS CONCRETE

Table 6. Summary of Degradation Model Variables and Values

Variable	Definition	Scenario	Min/ Mean/ Median/ Maximum	Reference
Hydrogen Evolution Rebar Corrosion				
H2RATE1	Rate of rebar corrosion due to hydrogen evolution (cm/yr) at high pH (before calcium leaching or carbonation penetrate to rebar).	Minimum	1E-5	(6)
		Baseline	8E-5	(6)
		Maximum	1.5E-4	(6)
H2RATE2	Rate of rebar corrosion due to hydrogen evolution (cm/yr) at low pH (after calcium leaching or carbonation penetrate to rebar).	Minimum	1E-4	(6)
		Baseline	5E-4	(6)
		Maximum	1E-3	(6)
Chloride Initiation of Oxygen-based Rebar Corrosion				
COV	Required clear cover over bars (cm).	Minimum	7.62	design drawings
		Baseline	6.03	design drawings
		Maximum	5.08	design drawings
CLSOIL	Chloride ion concentration in groundwater (ppm).	Minimum	0.44	(1), p. 2
		Baseline	1.3	(1), p. 2
		Maximum	5.3	(1), p. 2

WCR	Water to cement ratio (kg/kg).	Minimum	0.40	Assumed
		Baseline	0.44	(2), p.4
		Maximum	0.48	Assumed
Oxygen Corrosion of Rebar				
COV	Required clear cover over bars (cm).	Minimum	7.62	design drawings
		Baseline	6.03	design drawings
		Maximum	5.08	design drawings
O2DICONC	Oxygen diffusion coefficient in concrete (cm^2/s).	Minimum	2E-8	(1). p.4; from (2)
		Baseline	1E-7	(2), p. 4
		Maximum	2E-6	(2), p. 4
O2SOIL	Oxygen concentration in groundwater ($mole/cm^3$)	Minimum	1.25E-7	(1). p.4
		Baseline	2.47E-7	(1). p.4
		Maximum	3.125E-7	(1). p.4
Concrete Controlled Leaching				
CADICONC	Intrinsic diffusion coefficient of Ca++ in concrete (cm^2/s).	All	1E-7	(2), p. 4

CASOIIL	Ca++ concentration in ground-soil water (mole/cm^3).	Minimum	4.82E-7	(1), p. 7
		Baseline	2.35E-8	(1), p. 7
		Maximum	2.5E-9	(1), p. 7
CASOLID	Bulk Ca + + concentration in concrete solid (mole/cm^3).	Minimum*	0.0035	(2), p.4
		Baseline*	0.003	(2), p.4
		Maximum*	0.0025	(2), p.4
Geology-Controlled Leaching				
CADICONC	Intrinsic diffusion coefficient of Ca++ in concrete (cm^2/s)..	All	1E-7	(2), p.4
CAPORE	Ca + + concentration in concrete pore liquid (mole/cm^3).	All	2.7E-6	(2), p.4
CASOIL	Ca++ concentration in ground-soil water (mole/cm^3).	Minimum	4.82E-7	(1), p.7
		Baseline	2.35E-8	(1), p.7
		Maximum	2.5E-9	(1), p.7
CASOLID	Bulk Ca ++ concentration in concrete solid (mole/cm^3).	Minimum*	0.0025	(2), p.4
		Baseline*	0.003	(2), p.4
		Maximum*	0.0035	(2), p.4
DE	Effective dispersivity/diffusivity of Ca in geologic material (cm^2/s).	Minimum	1E-6	(2), p.5
		Baseline	2E-6	(2), p.5
		Maximum	3E-6	(2), p.5

RD	Retardation factor of Ca in geologic material (ml/cm^3).	minimum	2	(2). p. 4
		baseline	3	(2). p. 4
		maximum	5	(2). p. 4
Carbonation				
CODICONC	Diffusion coefficient of $C0_3$ in concrete (cm^2/s)	all	1E-7	(2)
CSOIL	Inorganic carbon content in the soil (mole/cm^3)	minimum	1.88E-7	(7)
		baseline	4.33E-7	(7)
		maximum	6.78E-7	(7)
CAOHCONC	Ca(OH)2 concentration in concrete (mole/cm^3)	minimum	0.0072	(2)
		baseline	.00148	Average
		maximum	0.00225	(2)
Sulfate Attack				
C3A	C3A content of concrete (weight %; e.g. 8 for 8%).	minimum	7	assumed
		baseline	8	(1), p. 6; (2). P. 4
		maximum	9	assumed
S04MGSOL	Sum of S04 and Mg concentrations in soil solution (mole/l).	minimum	1.51E-5	(1), p. 6
		baseline	1.08E-4	(1), p. 6
		maximum	3.77E-4	(1), p. 6

(1) Dicke, 1993.
(2) Walton and Dicke, 1993.
(3) Walton, Plansky, and Smith, 1990.
(4) Walton, J.C. 1993. Unpublished.
(5) Langton, Chris. 1993. Personal communication.
(6) Summarized from Grauer, et al., 1991, Hansson, 1985, Marsh and Taylor, 1988, and Morley, 1986.
(7) Seitz, 1993.
* CASOLID acts in opposite directions for geology-controlled and concrete-controlled leaching; therefore it is not possible to maximize or minimize both leach rates in the same simulation run.

Table 7. Summary of Rebar Stress (ksi) in ILT Baseline Scenario

Time (years)	Walls			Roof Spans		
	Bottom	Mid-Height	Top	Over Exterior Wall	Mid-Span	Over Interior wall
800	14.2	27.9	16.9	16.9	40.8	38.1
850	15.1	29.6	18.0	18.0	43.3	40.4
1,100	20.9	41.0	24.9	24.9	59.8	56.[illegible]
1,225	25.3	49.3	30.0	44.0	60.0	60.0
1,300	28.5	55.6	33.9	61.4	60.0	87.4

Table 8. Summary of Rebar Stress (ksi) in ILNT Baseline Scenario

Time (years)	Walls			Exterior Cell			First Interior Cell			Central Cells[1]		
	Bottom	Mid-Height	Top	Over Exterior Wall	Mid-Span	Over Interior Wall	Over Wall Towards Exterior	Mid-Span	Over Wall Towards Interior	Over Wall	Mid-Span	Over Wall
575	16.0	31.3	23.4	23.4	40.3	36.7	36.2	33.1	33.9	33.9	33.1	33.9
675	17.8	34.8	25.9	25.9	44.7	40.7	40.1	36.8	37.6	37.6	36.8	37.6
750	19.3	37.8	28.1	28.1	48.6	44.1	43.6	39.9	40.8	40.8	39.9	40.8
775	19.8	38.9	28.9	28.9	50.0	45.4	44.8	41.1	42.0	42.0	41.1	42.0
800	20.4	40.0	29.8	29.8	51.4	46.7	46.1	42.3	43.2	43.2	42.3	43.2
1,000	26.1	51.2	38.1	41.0	60.0	60.0	58.9	54.1	55.2	55.2	54.1	55.2
1,050	27.9	54.7	40.7	49.4	60.0	60.0	62.0	60.0	61.0	59.0	57.8	59.0
1,075	28.8	56.6	42.1	54.9	60.0	60.0				61.8	60.0	61.8
1,125	31.4	60.0	45.6	65.1	60.0	79.9						

Table 9. Summary of Baseline Results

Vault	Cracks Penetrate Roof (years)	Cracks Penetrate Walls (Mid-Height) (years)	Roof Collapse (years)
ILNT	570	800	1,045
ILT	790	1,080	1,300
LAW	1,420	22,235	3,100

Table 10. Summary of ILNT Vault Sensitivity Analyses

Scenario	Cracks Penetrate Roof	Cracks Penetrate Walls (Mid-Height)	Roof Collapse
Baseline	570	800	1,045
Hydrogen Evolution Corrosion Rate (Baseline = 513-4 cm/yr)			
1E-3	285	400	525
7.5E-4	380	535	700
2.5E-4	1,130	1,590	2,075
1E-4	2,775	3,000+	3,000+
Depth of Soil Cover (Baseline = 9 feet)			
8 feet	680	850	1,130
12 feet	400	590	925
16 feet	130	360	725
Rebar Size (Baseline = #8)			
#6	0	175	425
#7	250	485	735
#9	875	1,105	1,350
#11	1,785	1,965	2,150
#18	3,000+	3,000+	3,000+
Depth of Concrete Cover Over Rebar (Baseline = 2 3/8")			
1 ½"	600	825	1,060
3"	550	780	1,030
Concrete Strength (Baseline = 4,750 psi)			
3,000 psi	570	800	1,040
6000 psi	570	800	1,045

A "+" indicates that the event did not occur prior to the end of the simulation.

Table 11. Summary of ILT Vault Sensitivity Analyses

Scenario	Cracks Penetrate Roof	Cracks Penetrate Walls(Mid-Height)	Roof Collapse
Baseline	790	1,080	1,300
Hydrogen Evolution Corrosion Rate (Baseline = 5E-4 cm/yr)			
lE-3	395	535	655
7.5E-4	525	725	865
2.5E-4	1,560	2,155	2,565
lE-4	3,000+	3,000+	3,000+
Depth of Soil Cover (Baseline = 9 feet)			
8 feet	850	1,140	1,340
12 feet	625	940	1,180
16 feet	415	735	1,035
Rebar Size (Baseline = #8)			
#6	155	460	680
#7	470	770	1,180
#9	1,190	1,380	1,600
#11	1,950	2,185	2,340
#18	3,000+	3,000+	3,000+
Depth of Concrete Cover Over Rebar (Baseline = 2 3/8")			
1 1/2"	800	1,100	1,300
3"	775	1,075	1,290
Concrete Strength (Baseline = 4,750 psi)			
3,000 psi	790	1,080	1,300
6,000 psi	790	1,080	1,300

A "+" indicates that the event did not occur prior to the end of the simulation.

Table 12. Summary of LAW Vault Sensitivity Analyses

Scenario	Cracks Penetrate Roof	Cracks Penetrate Walls			Roof Collapse
		Top	Mid-Height	Bottom	
Baseline	1,420	2,015	2,235	2,300	3,110
Beam/Roof & Walls	Hydrogen Evolution Corrosion Rate (Baseline = 8E-5/5E-4 cm/yr)				
1.5E-4/lE-3	710	1,010	1,150	1,150	1,600
1.15E-4/7.5E-4	950	1,350	1,550	1,550	2,100
4.5E-5/2.5E-4	2,820	4,000	4,480	4,550	5,400
lE-5/lE-4	6,900	9,750	10,000+	10,000+	10,000+
Depth of Soil Cover (Baseline = 9 feet)					
8 feet	1,420	2,100	2,360	2,410	3,290
12 feet	1,420	1,900	2,185	2,235	2,610
16 feet	1,420	1,730	2,050	2,115	2,060
Walls/Roof Slab	Rebar Size (Baseline = #10/#6)				
#7/#5	1,120	1,100	1,325	1,400	3,110
#9/-	-	1,700	1,940	2,000	3,110
#14/#8	2,020	(3,150)	(3,410)	(3,450)	3,110
#18/#14	(3,800)	(4,440)	(4,710)	(4,750)	3,110
AASHTO Beam Size (Baseline = Type IV)					
Type III	0	2,015	2,235	2,300	2,700
Type V	1,420	2,015	2,235	2,300	3,430
Depth of Concrete Cover Over Rebar (Baseline = 2 3/8 ")					
1 ½"	1,420	2,015	2,250	2,300	3,110
3"	1,415	2,015	2,250	2,300	3,110
Concrete Strength (Baseline = 4,750 psi)					
3,000 psi	1,420	2,015	2,235	2,300	3,110
3,000 psi	1,420	2,015	2,235	2,300	3,110

A "+" indicates that the event did not occur prior to the end of the simulation.
Values in parentheses indicate that roof collapse will occur prior to the indicated crack penetration.

Table 13. Summary of Baseline Results Assuming High-pH Concrete

Vault	Cracks Penetrate Roof (years)	Roof collapse (years)
ILNT	1,200	1,840
ILT	1,375	2,225
LAW	Not available	

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ACRONYMS AND ABBREVIATIONS

ACI	American Concrete Institute
cm	centimeter
C3A	tri-calcium aluminate
EAV	E-Area Vaults
ft	feet
in	inch
ILNT	intermediate-level non-tritium
1LT	intermediate-level tritium
INEL	Idaho National Engineering Laboratory
kip	1,000 pounds
ksi	1,000 pounds per square inch
LAW	low-activity waste
LLWSB	Long-Lived Waste Storage Building
m	meter
mm	millimeter
ppm	parts per million
psi	pounds per square inch
s	second
SRS	Savannah River Site
WSRC	Westinghouse Savannah River Company
yr	year

APPENDIX: QUALITY ASSURANCE

This Appendix is divided into three parts. First, the implementation of the Project Quality Assurance Plan is discussed. Next, the letter report describing INTERA's plan and procedures for software and technical reporting quality assurance for the E-Area Vaults Degradation Study is provided. Finally, forms used in maintaining Quality Assurance Control during the project are provided.

A.1 IMPLEMENTATION OF THE PROJECT QUALITY ASSURANCE PLAN

The RCPC.DHelper models (Furlong, 1991) used as the basis for the structural analysis portion of this study are available commercially through the American Concrete Institute Software Sales Department. The programs have been in use for the past 4 years by approximately 300 engineering offices.

The RCPC computer software for the analysis of reinforced concrete structures has formed the basis for this project. This software has been validated by the author. The software is divided into five main subroutines which do not interact, with each subroutine appropriate for a particular application. For the E-Area Vaults, the "Continuous Beams" program was utilized. This program was tested by using a sample data set available in the manual (Furlong, 1991), and comparing the computed results with results printed in the manual. All results were identical. Another program, NAWY10, was used to analyze the time-dependant loss of prestress in the AASHTO beams. In the same way, a sample data set available in the manual (Nawy, 1989) was used for testing the program. Computed results matched results printed in the manual.

There were four main revisions to the RCPC code:

1 Original program was designed for screen-based input and output. In order to facilitate the multiple runs necessary for the sensitivity analysis and calculation of stress levels through time, the program was modified to utilize file-based input and output.

2. Degradation subroutine was added.

3. A time loop was added to recursively calculate the vault condition through time.

4. For the LAW vault case, a section was added to compute the stress due to curvature and the depth of the neutral axis in the roof slab.

After the code was modified to utilize file-based input and output, an additional test was performed using the manual-supplied input and output. In addition, a data set was created appropriate for the E-Area Vaults. This data set was run in both the original model and in the modified model. Again, all results were identical.

Next the degradation subroutine and time loop were added. Degradation model components included:

- Time to depassivation of rebar.
- Oxic corrosion of rebar.
- Anoxic ("hydrogen-evolution") corrosion of rebar.
- Sulfate attack.
- Calcium hydroxide leaching.
- Carbonation.
- Calculation of fracture aperture and spacing.

Testing of this modification consisted of two phases. First, results of the degradation model were compared to results obtained by modeling performed at INEL. There were extremely slight differences between INEL model results and INTERA results, easily attributed to rounding error. Next, testing was performed on the structural component of the code. The time zero results for the code were compared to the results obtained from the unmodified RCPC code. Because no degradation has taken place at time zero, these results should be, and were, the same. For the LAW vault modifications to calculate stress due to curvature in the roof, testing was performed by comparing model results to spreadsheet calculations.

All changes are documented in detail within the modified code, both at the point of modification and, in chronological order, at the top of the code.

Performance and Design Specifications were generated for the modifications to the RCPC.DHelper code, in order to incorporate concrete degradation, and were established as controlled documents (i.e., they were approved by the program manager and quality assurance manager and had a control date assigned). Performance and Design Specifications for RCPC.DHelper and NAWY10 were taken from the documentation for these codes and established as controlled documents. Performance Specifications for both acquired codes and modifications included the following components:

- a general description of RCPC.DHelper, NAWY10, and modifications to the RCPC.DHelper code, and the intended use of information expected from the codes, including relevant contract specifications.
- a description of physical and chemical phenomena accounted for and any important phenomena neglected.
- statement of relevant mathematical equations and derivations.

- statement and rationalization of applicable assumptions, limitations and simplifications.

- a general description of the type of output information.

- a general description of the type of input information.

- references.

Design Specifications for both acquired codes and modifications included the following components:

- Description of numerical techniques used to solve governing equations.

- Statement of relevant discretized (or otherwise transformed for numerical solution) equations and derivations.

- Statement and rationalization of applicable assumptions and limitations.

- Description of the structure and organization of the computer programs, including logic flow.

- Description of program input and output.

- Description of code/system interfaces.

- Glossary of model variables.

RCPC.DHelper and NAWY10 software was baselined (i.e., entered into the Control File Index at our Austin, TX headquarters). Modifications to software were identified, documented, and tracked through the Control File Index. All data and results which were used in formal code testing and applications were baselined. The project report was baselined and subjected to internal (i.e., within INTERA) review before being submitted to WSRC. The review was documented in the form of required changes, recommended changes and other observations, in writing on a copy of the draft document. After changes were made in response to the internal review, the report was again baselined and submitted to WSRC with the subtitle "Draft Report." All comments in response to WSRC review were received verbally only. Therefore, INTERA prepared a memo summarizing the review comments and distributed copies to WSRC and to the Control File Index at INTERA headquarters. After response to WSRC comments was completed, the report was again baselined and submitted to WSRC as the final report for this Task #7.

A.2 PROJECT QUALITY ASSURANCE PLAN

Mr. Shawn Reed
WSRC
Savannah River Technology Center
Solid Waste Engineering
#742-7G
Aiken, SC 29802

May 20, 1993

Re: Quality Assurance Procedures for Software and Technical Reports Under Contract #AA20180P-Task Order 7

Dear Mr. Reed:

The following letter report describes INTERA'S plan and procedures for software and technical reporting quality assurance for the E-Area Vaults Degradation Study. This letter report is intended to satisfy Paul Lowe's request at the May 10 status meeting for a summary QA plan for the structural analysis software currently being used on this project and report deliverables. Software for this project has been developed primarily outside of INTERA. The software is two structural analysis codes for concrete structures obtained from the University of Texas at Austin and Rutgers University. Through a co-operative effort between the code authors and INTERA-AUGUSTA the codes are currently being modified to allow, (1) input of concrete thickness and re-bar spacing, (2) the use of file handling for input and output rather than the interactive default mode, and (3) chemical degradation of the reinforced concrete.

The QA plan and procedures for computer software and report deliverables have been taken from INTERA'S Project Quality Assurance Manual prepared for the Westinghouse Savannah River Company (Draft; December 20, 1990). This NQA-1 manual has been submitted for approval with WSRC, however this approval is pending. We anticipate a review of the manual prior to the end of the current fiscal year.

PART A PROJECT QUALITY ASSURANCE PLAN

Quality assurance calls for baselining software and supporting documentation through the assignment of Control Identification Numbers (CIN's) and entry into the project Control File Index (CFI). The QA plan requires, for codes developed outside Of INTERA, review, verification, validation (when possible) and documentation of software modification activities. Changes to baselined software shall also be identified and tracked through the CFI and shall be subject to review, approval, verification and validation as appropriate. Changes to baselined software shall require documentation and this documentation shall be entered into the CFI. In addition, procedures for the revision of baselined software shall require identification of any baselines which might require changes as a result of the revision, and that users of affected software be notified of any revisions.

INTERA shall verify the suitability of previously developed computer codes by:

1. Reviewing previous applications of the code(s);

2. Performing a validation of the code(s) for the contract application by inputting data representative of the application;

3. Exercising the code(s) under expected use conditions; and

4. Evaluating the limitations of the code(s).

Results of the validation process shall be documented and entered into the project CFI. A summary report of the results shall be provided to the client.

The structural analysis code(s) adapted for this project are considered proprietary to the author, Dr. Richard Furlong, University of Texas at Austin and Dr. Edward Nawy, Rutgers University. The source code and documentation have been provided to INTERA for adaptation and use on this project without cost to WSRC.

PART B PROJECT QUALITY ASSURANCE PROCEDURES

TITLE: QA Control File and Index

The INTERA - AUGUSTA staff will be responsible for preparing and documenting records that will enter the QA Control File at our Corporate Headquarters in Austin. We will also be responsible for filing QA documents and documentation of client communications with the QA Administrator in Austin.

The INTERA - AUSTIN QA Administrator will be responsible for reviewing control documents, maintaining proper records storage, and maintaining the Control File Index.

TITLE: Baselining and Revising Baselined Specifications

Performance, Design, and Test Specifications shall be baselined for the major codes acquired and applied on this project.

When revising a code, Performance, Design, and Test Specifications shall be developed, baselined, and established as controlled documents (i.e., be approved by the program manager and quality assurance manager and have a control date assigned).

An example of a QA Control Document which shall be completed for Specifications has been included as an attachment.

TITLE: Baselining and Revising Baselined Codes

All structural analysis codes shall be documented following acquisition for the project and during modification and testing. The documentation of the unmodified code(s) shall include: Test Data, Test Results, Validation History (if any), Code Abstract and Users Manual. Modifications which are completed by INERA-AUGUSTA to the codes to allow, (1) the use of file handling for input and output rather than the interactive default mode, and (2) chemical degradation of the reinforced concrete will be documented with brief performance specifications, design specifications, and a comparison of the code output with empirical results from INEL.

In addition, each code should be accompanied by the following documentation, as appropriate: Code Name and Version Number, Brief Description of Code, Original Source Code and Original Author(s), Brief History of Major Modifications, Proprietary Details, Disclaimer, Language and Level, Machine Where Operative, and References.

An example of a QA Control Document which shall be completed for Computer Codes has been included as an attachment.

TITLE: Baselining and Revising Baselined Test. Application and Other Data

All data which are to be used in formal (i.e., documented) code testing or in code applications shall be baselined. Data should be characterized in detail. The documentation should include, at a minimum, the following: source and method of acquisition, appropriateness for the intended model application, and derivation of input data (processed data) from raw data.

All test and application data baselines shall be written to diskette with copies furnished to the QA Administrator.

Baseline data shall be revised as necessary to correct problems or to improve/ensure quality. Revised baselines shall include justification for the revision.

An example of a QA Control Document which shall be completed for Test/Application/Other Data has been included as an attachment.

TITLE: Baselining and Revising Baselined Test Results

All output data from the code testing phase shall be baselined. Testing of the unmodified structural analysis codes shall be limited to execution of the test problem provided with the code on the PC with which the structural analysis is to be completed. A formal review by the project engineer of the Test Results shall be completed to ensure the accuracy of the installed code.

Testing of the code modifications concerning deterioration of the reinforced concrete shall be limited to accurate reproduction of empirical data provided by INEL. Formal testing shall be reviewed by person(s) not involved in the modification of the code(s). Test Results shall be analyzed for satisfaction of Test Specifications.

The Test Results, and the analyses thereof, must be documented and baselined. A print-out of the Test Results and the Test Data shall be filed with the QA Administrator when Results are baselined.

An example of a QA Control Document which shall be completed for Test/Application Results has been included as an attachment.

TITLE: Baselining Application Results

The results of all code applications to be transmitted outside of, or relied upon by, INTERA or which yield significant information about the code's capabilities or limitations, or about measured data, or about the system or process being modeled shall be baselined.

Where possible input data should be printed in conjunction with the corresponding Application Results output. A copy of the Application Results and Application Data shall be filed with the QA Administrator when results are baselined.

TITLE: Baselining and Revising Baselined Technical Reports and Code Documentation

All Reports which are considered deliverables shall be baselined before transmission outside Of INTERA. Code Documentation shall be baselined for internal control. For proprietary reasons, these Baselines will not be allowed outside of INTERA.

Topical Reports and Letter Reports which are specified as contract deliverables shall undergo formal technical review. Baselined reports shall be revised as necessary to correct problems, improve quality, or expand scope.

An example of a QA Control Document which shall be completed for Report/Code Documentation has been included as an attachment.

TITLE: Technical Reviews

Each Technical Report, Model Documentation Report, Letter Report, or other document containing technical information that is a project deliverable prepared to satisfy contract requirements shall be the subject of one of more technical reviews before being transmitted outside INTERA.

Documents and data shall be baselined before being submitted for technical review.

Reviews of reports and other documents should consider, as a minimum, the following items:

- Organization, clarity, and conciseness of the material presented;
- Correctness of any assumptions that are made;
- Adequacy of the discussion of variables;
- Validity of the conclusions and recommendations;
- Adequacy of illustrations, graphs, tabular data, etc.; and
- Appropriate acknowledgement of contributions and referenced material.

Reviews shall be documented with written comments in the form of required changes, recommended changes, and other observations. The review shall also document the material being reviewed (title or description), the author of the material, date of the review, and persons performing the review.

Review comments must be stated in terms which will clearly convey the meaning of the comment to others knowledgeable on the subject.

Review comments may be in the form of annotations on the document being reviewed if the comment can be adequately recorded in this manner. When such annotation is inadequate or inappropriate, the comment(s) shall be recorded on separate sheets.

Each review comment shall be responded to and resolved and the response/resolution shall be documented. When review comments are recorded on the document being reviewed, responses may also be recorded on the document.

All review comments recorded on separate sheets shall be responded to either on the review sheets or on separate sheets.

Editorial recommendations may be acknowledged in summary fashion, e.g., "implemented where possible".

When the technical reviewer is unable to accept the task manager's response to one or more required changes, the program manager shall be called upon to resolve the issue unless the program manager is involved in the disagreement, in which case one of the program manager's peers shall resolve the issue.

An example of a QA Control Document which shall be completed for Technical Reviews has been included as an attachment.

cc: Paul Lowe
Jim Cook
Keith Dykes

APPENDIX E

GEOCHEMICAL INTERACTIONS

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APPENDIX F

SOFTWARE QA PLAN

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The information in this appendix is identical to that in Appendix E of the CSEW report (DOE 1999b).

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APPENDIX G

RESULTS OF FLOW AND TRANSPORT MODELING

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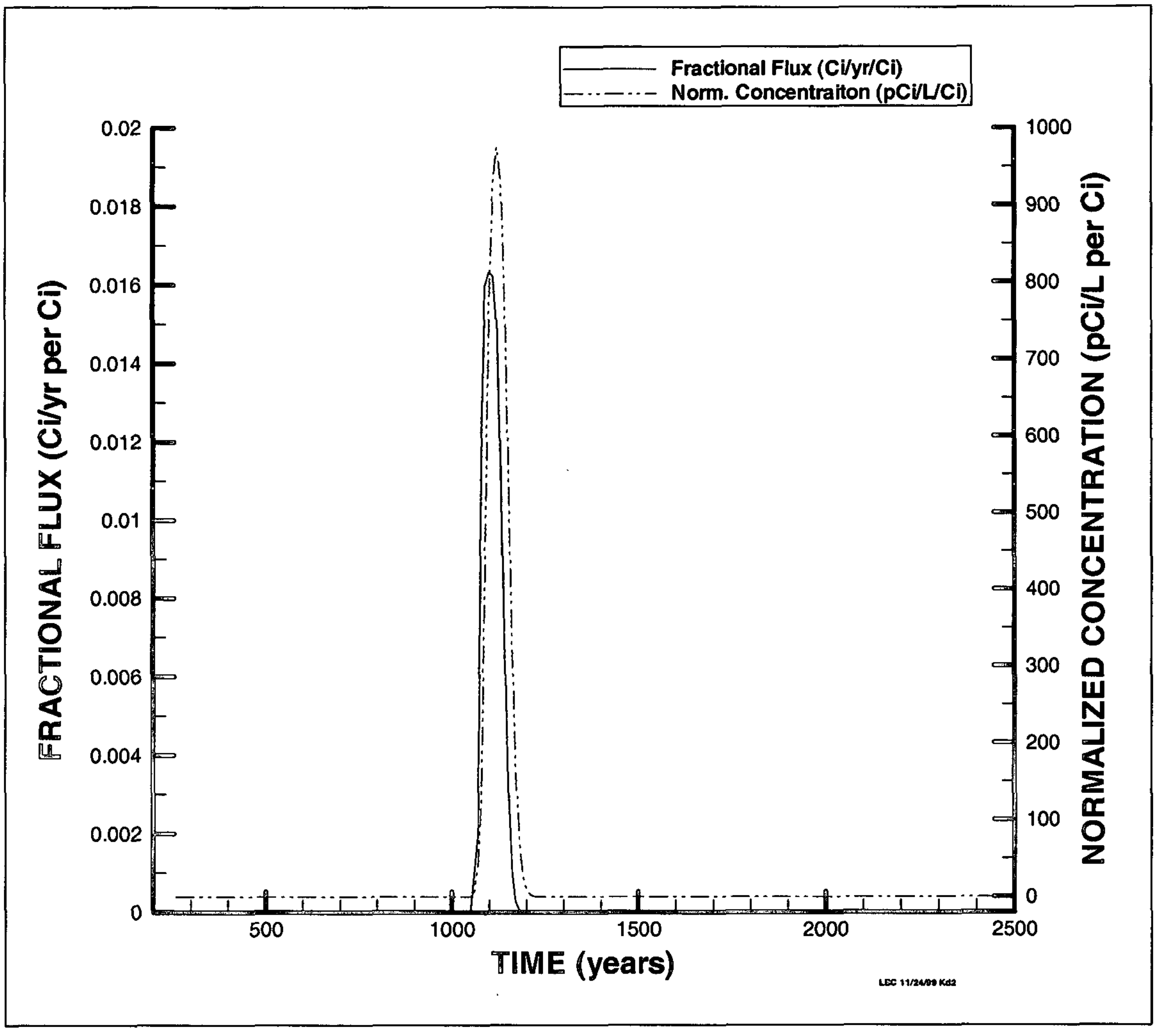

Figure G-1. Hypothetical waste (Kd=2 ml/g): PORFLOW predicted I-129 fractional release (Ci/year/Ci inventory) to the water table and normalized concentration (pCi/L/Ci inventory) at the 100-meter well for the Intermediate Level Vaults

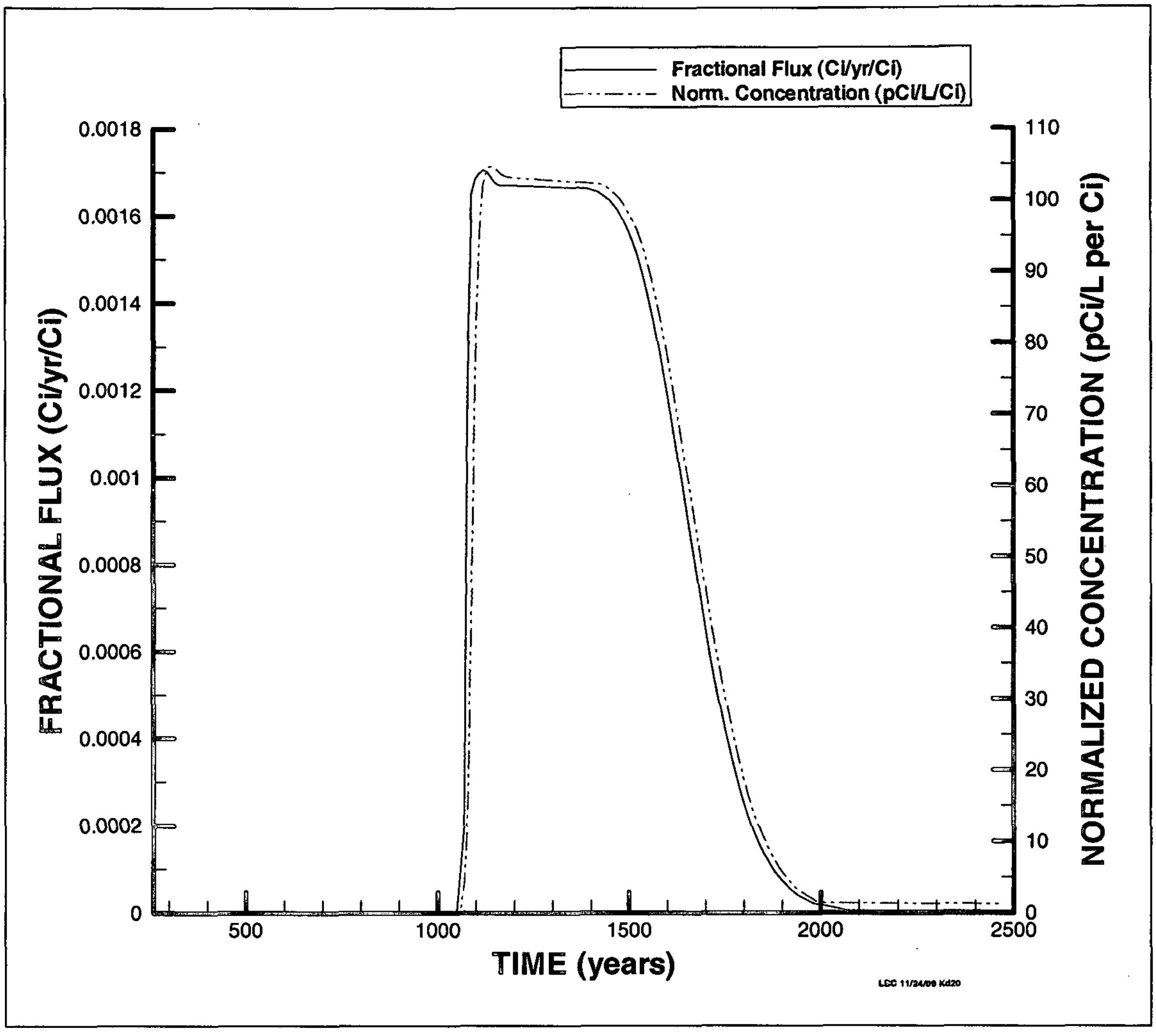

Figure G-2. Hypothetical Waste (Kd=20 ml/g): PORFLOW predicted I-129 fractional release (Ci/year/Ci inventory) to the water table and normalized concentration (pCi/L/Ci inventory) at the 100-meter well for the Intermediate Level Vaults

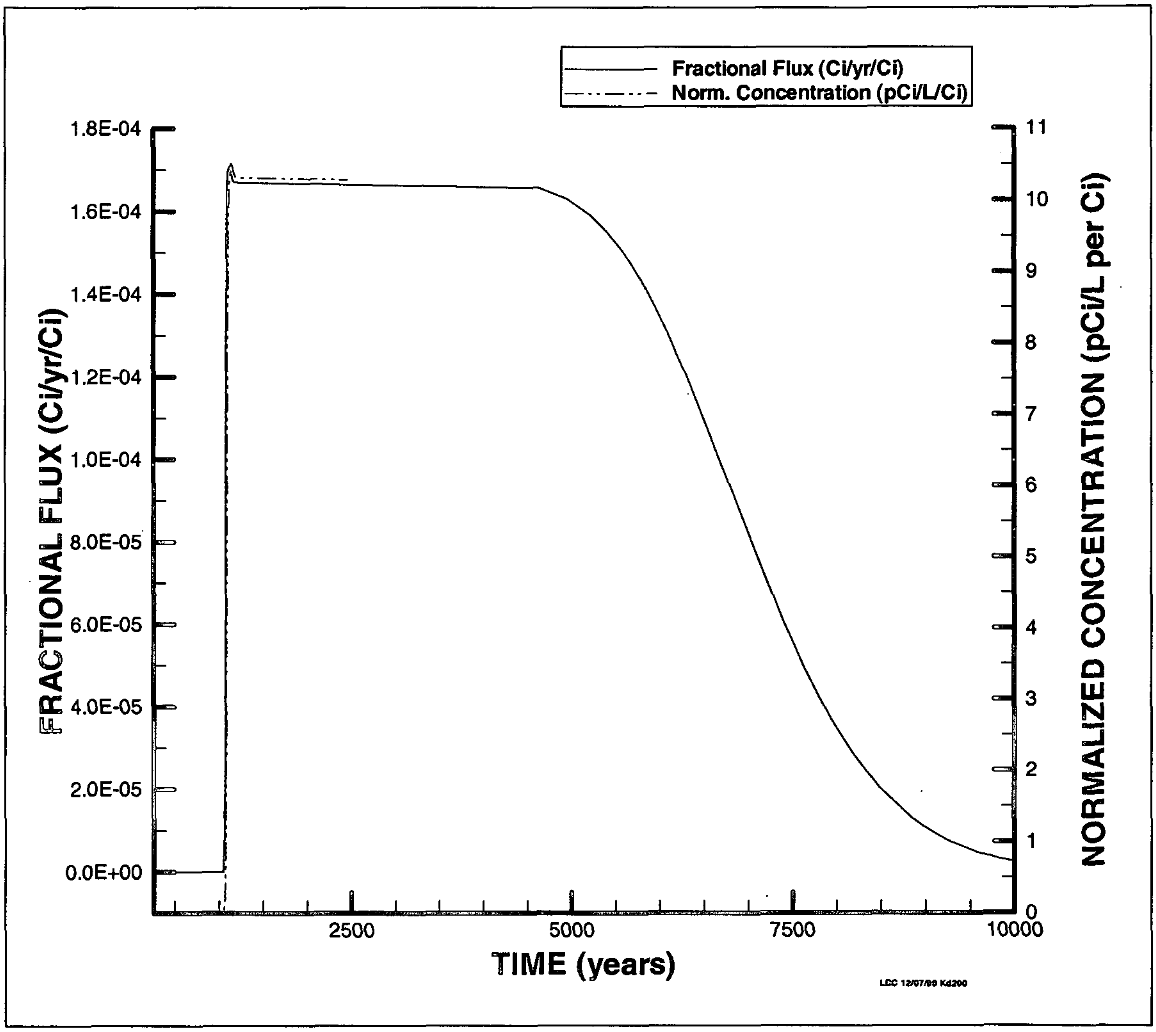

Figure G-3. Hypothetical Waste (Kd=200 ml/g): PORFLOW predicted I-129 fractional release (Ci/year/Ci inventory) to the water table and normalized concentration (pCi/L/Ci inventory) at the 100-meter well for the Intermediate Level Vaults

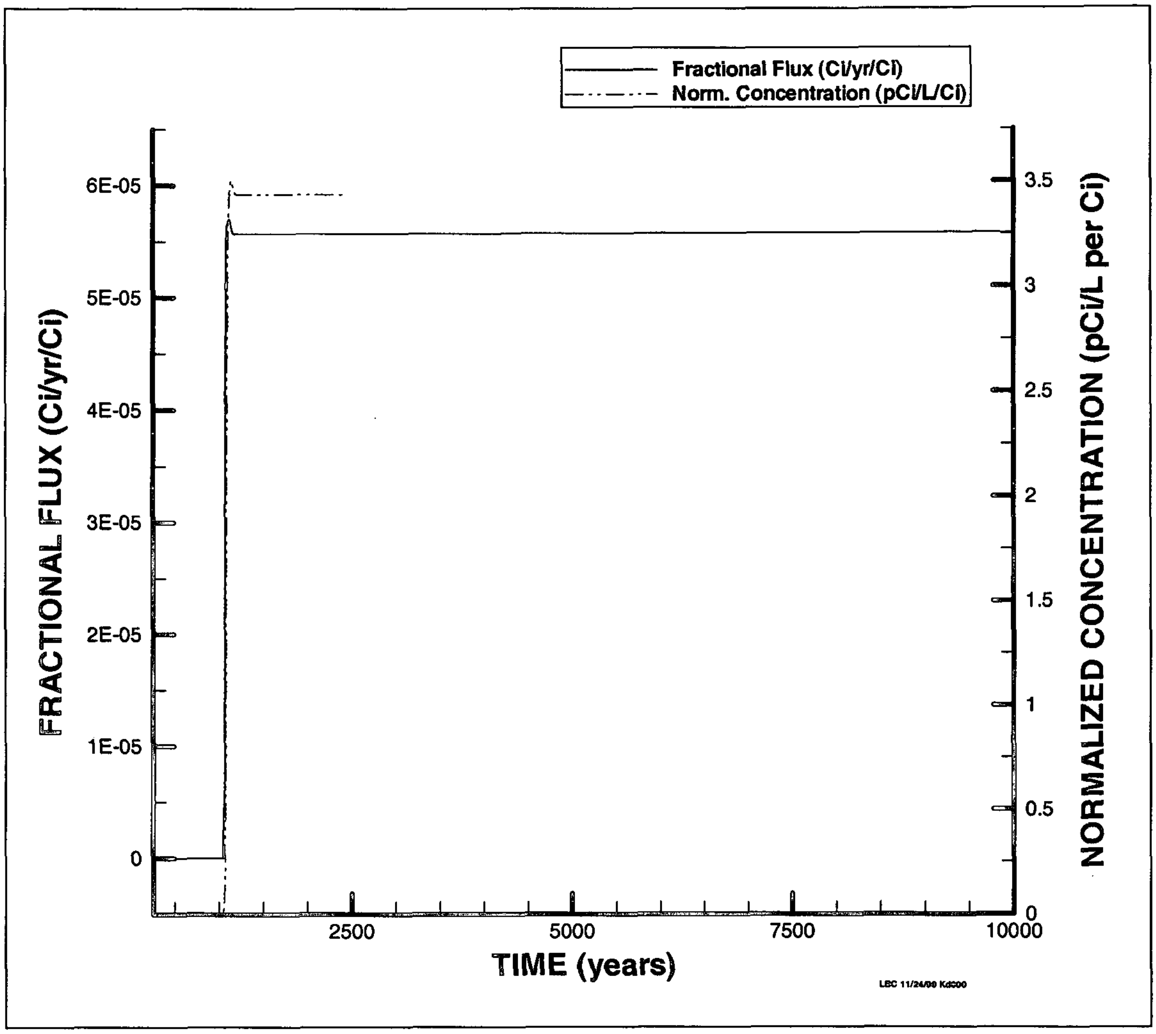

Figure G-4. Activated Carbon (Kd=600 ml/g): PORFLOW predicted I-129 fractional release (Ci/year/Ci inventory) to the water table and normalized concentration (pCi/L/Ci inventory) at the 100-meter well for the Intermediate Level Vaults

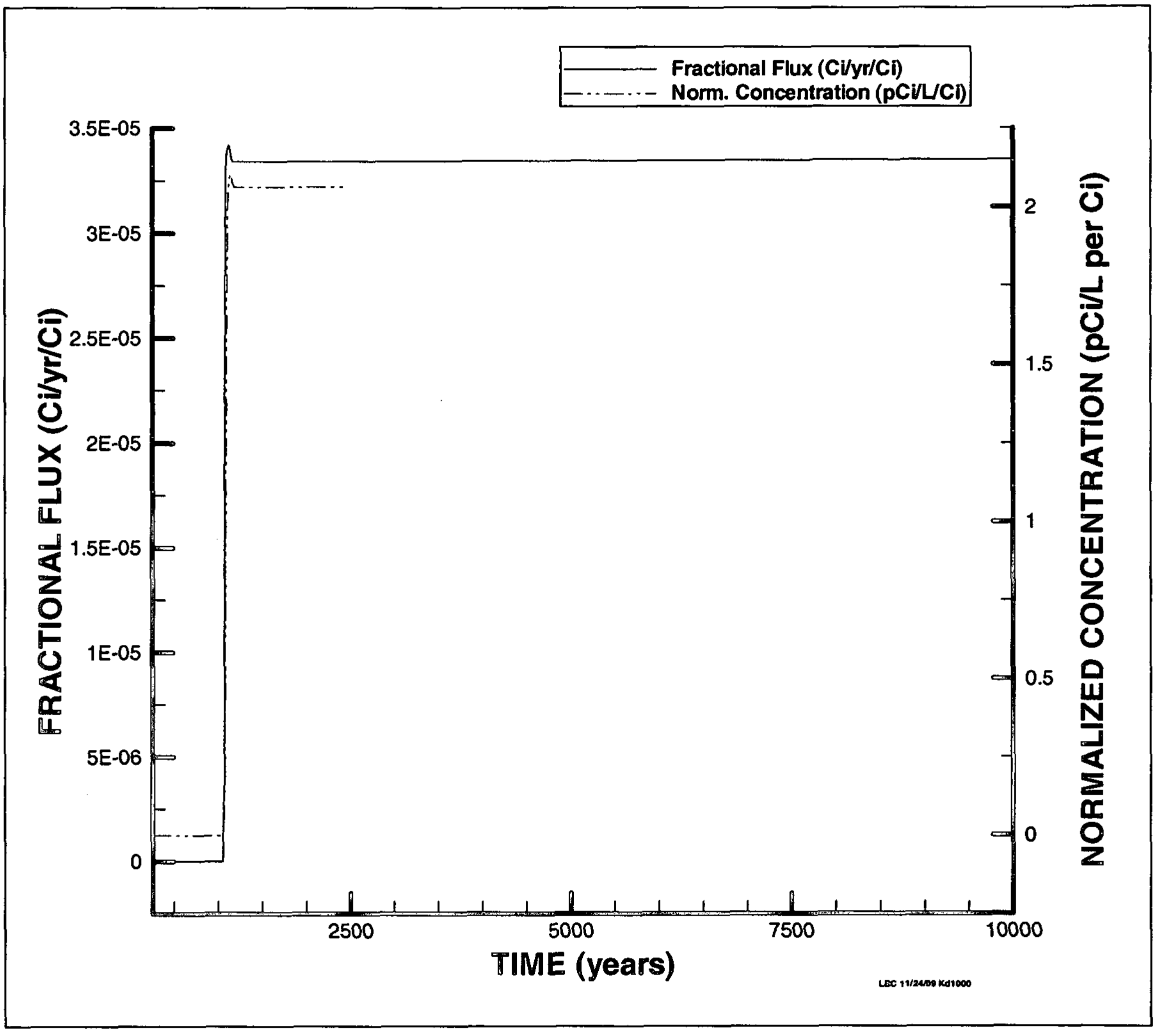

Figure G-5. Hypothetical Waste (Kd=1000 ml/g): PORFLOW predicted I-129 fractional release (Ci/year/Ci inventory) to the water table and normalized concentration (pCi/L/Ci inventory) at the 100-meter well for the Intermediate Level Vaults

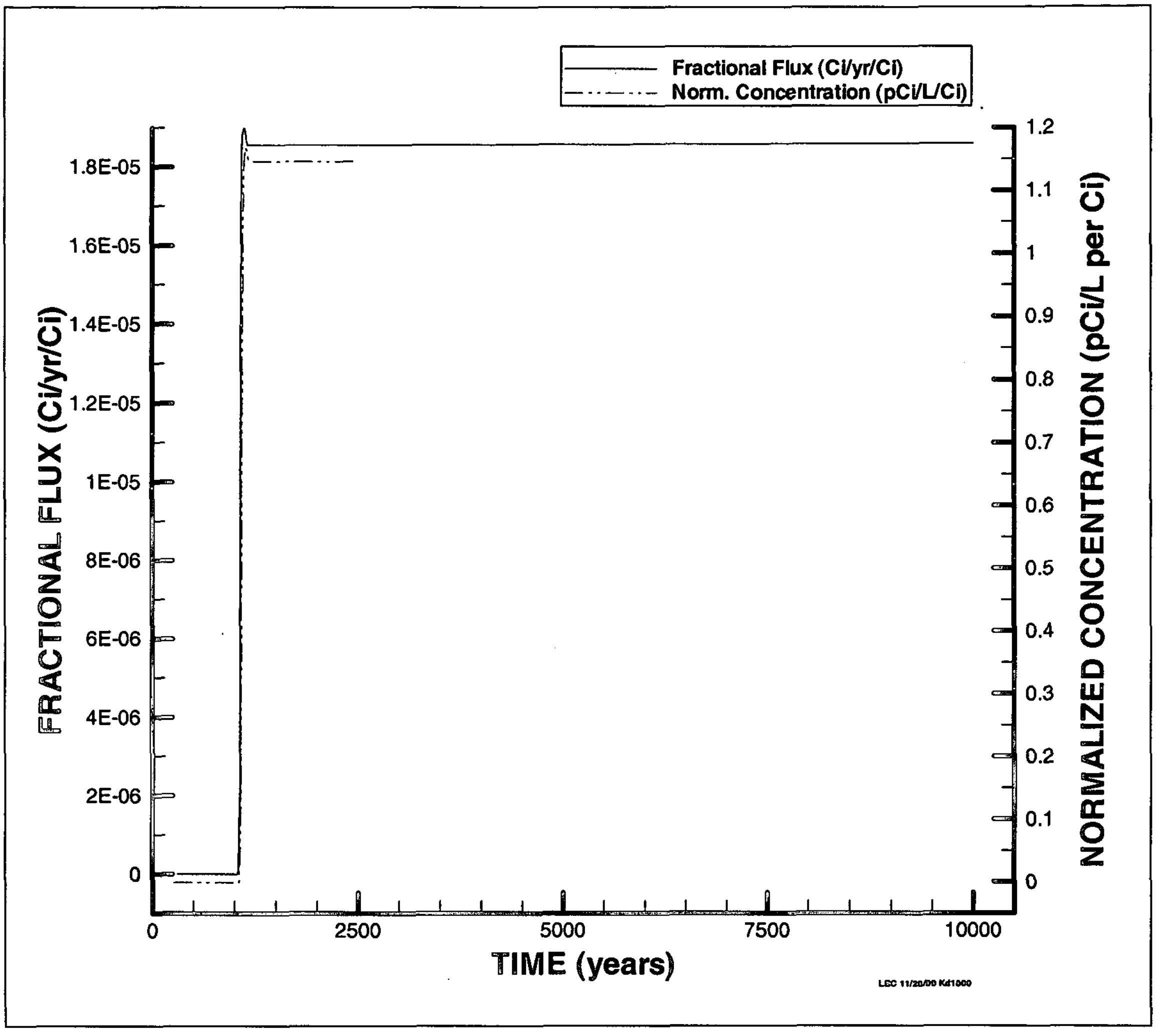

Figure G-6. Dowex 21K Resin[a] (Kd=1800 ml/g): PORFLOW predicted I-129 fractional release (Ci/year/Ci inventory) to the water table and normalized concentration (pCi/L/Ci inventory) at the 100-meter well for the Intermediate Level Vaults

[a] Not planned for disposal in IL Vaults

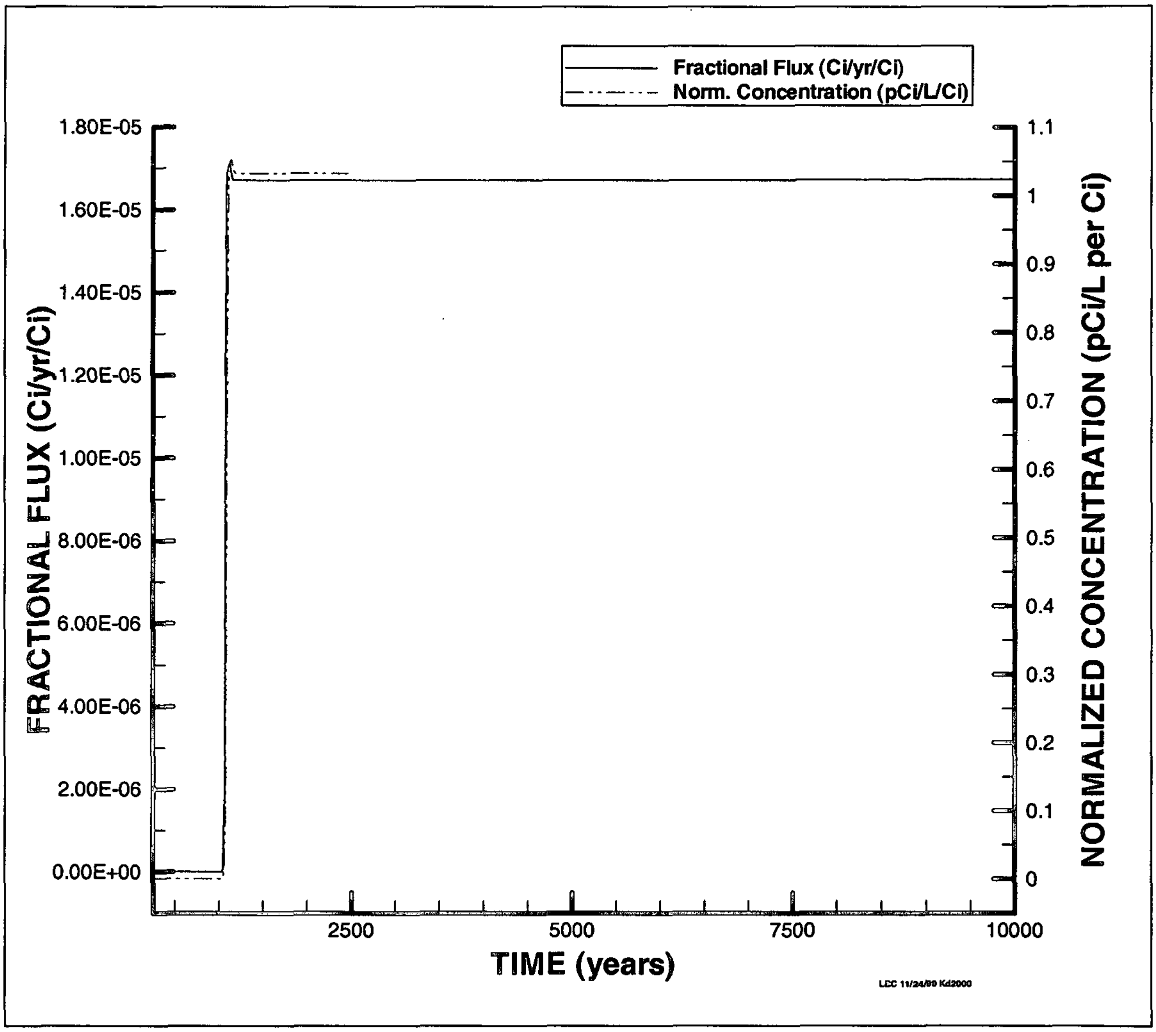

Figure G-7. Hypothetical Waste (Kd=2000 ml/g): PORFLOW predicted I-129 fractional release (Ci/year/Ci inventory) to the water table and normalized concentration (pCi/L/Ci inventory) at the 100-meter well for the Intermediate Level Vaults

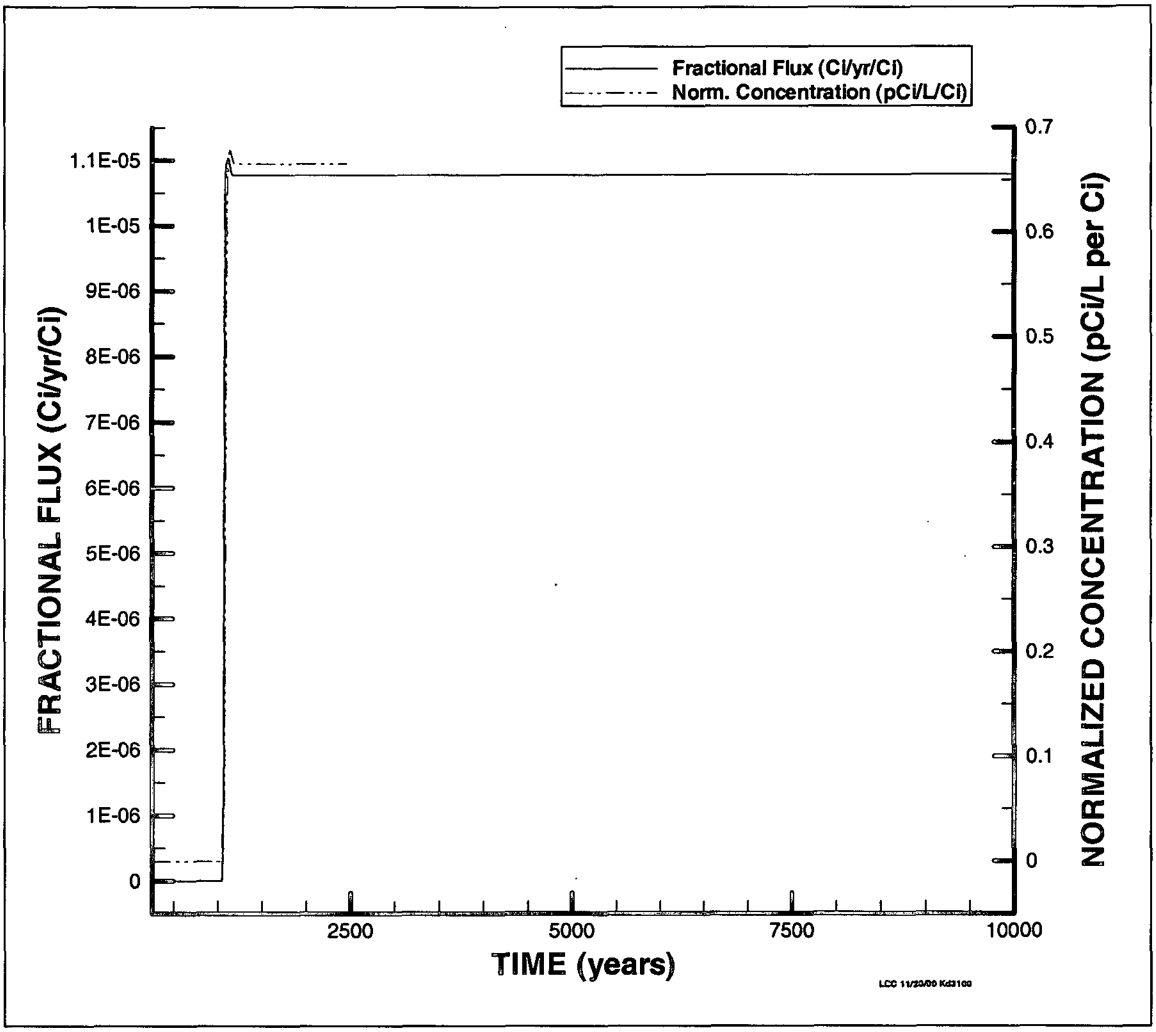

Figure G-8. GT-73[a] (Kd=3100 ml/g): PORFLOW predicted I-129 fractional release (Ci/year/Ci inventory) to the water table and normalized concentration (pCi/L/Ci inventory) at the 100-meter well for the Intermediate Level Vaults

[a] Not planned for disposal in IL Vaults

APPENDIX H

SENSITIVITY/UNCERTAINTY ANALYSIS FOR GROUNDWATER

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The information in this appendix is identical to that in Appendix G of the CSEW report (DOE 1999b).

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