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

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

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ACRONYMS AND ABBREVIATIONS

BBI	Best Basis Inventory
CoC	Constituents of concern
DFLAW	Direct Feed Low Activity Waste
DOE	Department of Energy
DOT	Department of Transportation
DST	double shell tank
EIS	Environmental Impact Statement
EM	DOE Office of Environmental Management
ETF	Effluent Treatment Facility
FFRDC	Federally Funded Research and Development Center
FWF	Federal Waste Disposal Facility
GAO	Government Accounting Office
HLW	high level waste
ICV	In-Container Vitrification™
IDF	Integrated Disposal Facility
INL	Idaho National Laboratory
IP	industrial package
LANL	Los Alamos National Laboratory
LAW	Low Activity Waste
LAWPS	Low Activity Waste Pretreatment Facility
LDR	Land Disposal Restrictions
LERF	Liquid Effluent Retention Facility
LSA	Low specific activity
LWS	Liquid Secondary Waste
NAS	National Academies of Science, Engineering and Medicine
NDAA	National Defense Authorization Act
ORNL	Oak Ridge National Laboratory
PA	Performance Assessment
PE	Performance Evaluation
PNNL	Pacific Northwest National Laboratory
PT	Pretreatment Facility
PUREX	Plutonium Uranium Extraction
RCRA	Resource Conservation and Recovery Act
R&D	Research and development
REDOX	REDuction and OXidation
SLAW	Supplemental Low Activity Waste
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SST	single shell tank
TCLP	Toxicity Characteristic Leaching Procedure
WAC	Waste acceptance criteria
WCS	Waste Control Specialists
WTP	Waste Treatment and Immobilization Plant
WVDP	West Valley Demonstration Project

EXECUTIVE SUMMARY

INTRODUCTION

Section 3134 of the National Defense Authorization Act for Fiscal Year 2017 (NDAA17) stipulates that a Federally Funded Research and Development Center (FFRDC) team conduct an analysis of technologies for treating and solidifying what is generally called "Supplemental Low Activity Waste" at the Department of Energy's Hanford Nuclear Reservation. The focus of the analysis is technical, and the FFRDC team is made up of technical experts in appropriate disciplines from the national laboratories. The NDAA17 also requires a concurrent review of the analysis by a committee of technical experts selected by the National Academies of Science, Engineering, and Medicine.

Hanford tank waste processing is currently planned to complete in 2063. Supplemental Low Activity Waste (SLAW) refers to approximately 54,000,000 gallons of Hanford liquid radioactive waste that cannot be treated and solidified by the currently planned treatment systems without extension of processing and tank storage durations. A decision on how to treat the SLAW has not been finalized.

There is a long history related to tank waste treatment at Hanford dating back decades. This report is not intended to provide a detailed history but focuses on the current challenges related to SLAW and describes the results of the FFRDC analysis that are intended to inform the decision-makers who will select the treatment technology. This study addresses many factors to be considered by the decision-makers, including technical feasibility and costs. Costs are estimated to vary from approximately $2B to $36B.

SUPPLEMENTAL LOW ACTIVITY WASTE

For treatment and disposal, Hanford tank wastes will be divided into a High Level Waste (HLW) stream and a Low Activity Waste (LAW) stream. The amount of existing LAW and LAW generated during operation of the Hanford Waste Treatment and Immobilization Plant (WTP) will exceed the planned processing capacity of the WTP LAW vitrification facility. River Protection Project System Plan 8 (October 2017) estimates that the WTP LAW treatment capacity will be exceeded by approximately 54,000,000 gallons over the life of the tank treatment mission. This "excess," or "supplemental" LAW will require treatment external to the WTP process. The liquid SLAW must be solidified by a treatment technology before it can be permanently disposed of in a landfill for radioactive wastes.

The SLAW can be characterized as a "mixed" radioactive waste. Compared to the HLW stream, the radioactivity of the SLAW is low, averaging just seven one-thousandths of a curie per gallon. Even though the average activity is relatively low, some of the SLAW may be difficult to dispose of because it contains radionuclides that are long-lived and mobile in the environment, such as technetium-99 (Tc-99) and iodine-129 (I-129).

Some of the metals and organic chemicals suspected to be in the SLAW are regulated under the Resource Conservation and Recovery Act (RCRA) that sets "Land Disposal Restrictions," or LDRs. Other constituents, such as nitrates, are regulated to prevent groundwater contamination.

These radionuclides, metals, nitrates (and other groundwater contaminants), and organics may fail to meet regulatory requirements if not adequately immobilized/contained by the wasteform/disposal system or destroyed by the treatment processes. This study evaluated the ability of the wasteforms and immobilization processes to adequately treat each of these constituents.

TECHNOLOGIES ANALYZED

The three immobilization technologies identified in the NDAA17 for analysis are vitrification, grouting, and fluidized bed steam reforming:

Vitrification – This high temperature technology blends the liquid SLAW with glass-forming materials at approximately 1150 °C, forming a mixture that incorporates most of the radionuclides and metals into a “primary” glass wasteform. The vitrification and offgas systems destroy the LDR organic compounds and some of the nitrates. Because the water in the SLAW is not be incorporated into the glass, all the water is managed as liquid “secondary” waste. The solid secondary wastes from the vitrification process are planned to be grouted prior to disposal, while the liquid secondary wastes will be treated and the water released and any contaminants captured and grouted.

Grouting – This technology operates at room temperatures and blends the liquid SLAW with dry inorganic materials to produce a cement-like wasteform. All radionuclides, metals, nitrates, and organics are incorporated into the grout, except for very small amounts that could partition to the process offgas and filters. The secondary wastes are minimal because the water in the SLAW is chemically incorporated into the wasteform. Pretreatment processes or waste feed alterations may be required to destroy or reduce the LDR organic compounds.

Fluidized Bed Steam Reforming – This high temperature technology blends the liquid SLAW with dry inorganic materials at approximately 750 °C, forming dry granular mineral particles with a chemical structure that retains the radionuclides and metals. No liquid offgas system secondary wastes are produced, and the primary wasteform contains nearly all the radionuclides. Solid secondary wastes (spent carbon sorbent and air filters) are similar to those from vitrification but have less radioactivity. FBSR is expected to destroy the LDR organic compounds and nitrates.

DISPOSAL LOCATIONS ANALYZED

This study analyzed disposal of the immobilized SLAW in two disposal locations, one onsite at the Hanford Reservation and another located outside the State of Washington. The waste acceptance criteria (WAC) are specific to each disposal site; the differences impact the required treatment technologies for SLAW. LDRs must be addressed for onsite and out-of-state disposal. Details of how these disposal locations were analyzed are described in the report.

SLAW wasteforms were analyzed for compliance with disposal site WAC. The onsite WAC are restricted to vitrified primary wasteforms; therefore, the FFRDC team conducted a Performance Evaluation (PE) of long-term behavior of primary and secondary wasteforms in the onsite disposal facility. The PE used software, input parameters, and timeframes consistent with those used for the formal Performance Assessment (PA) for onsite disposal at Hanford to analyze the ability of grouted and steam-reformed wasteforms to meet the same performance criteria. This evaluation examined and simulated the behavior of long-lived isotopes, including Tc-99- and I-129, over time. See full discussion of the PE in Appendix F, “Disposal.”

CASES ANALYZED

Five cases were developed for analysis, as shown in Table 1. Out-of-state disposal of vitrified SLAW was not analyzed because disposal of vitrified SLAW onsite is already the “baseline” case. Out-of-state disposal of vitrified SLAW would add additional cost without additional benefit.

Table 1 High-level comparison of the five cases selected with disposal siting and pretreatment assumptions

Five Cases Analyzed	Primary Waste Disposal Facility	Secondary Waste Disposal Facility	Additional Pretreatment
Vitrification	Onsite	Onsite	None
Grouting Case 1	Onsite	Onsite	LDR organics
Grouting Case 2	Out-of-state	Onsite	LDR organics
Steam Reforming Case 1	Onsite	Onsite	None
Steam Reforming Case 2	Out-of-state	Out-of-state	None

These five cases were analyzed using the criteria specified in NDAA17: risks, benefits, costs, schedules, regulatory compliance (for onsite and out-of-state disposal), and obstacles to implementation. The potential need for further processing of the LAW to remove long-lived radioactive constituents is addressed in the pretreatment section of the report, and risks and obstacles are combined.

A semi-quantitative Risk Analysis assessed program risks and consequences associated with each of the SLAW cases as related to cost and schedule. In conducting the Risk Analysis, the FFRDC team recognized system-level risks applicable to all 5 cases that were likely outside the control of the SLAW program to manage (e.g., sufficient Congressional appropriations). The team did not attempt to quantify the consequences of those cross-cutting risks. See full discussion of Risk Assessment in Appendix E.

CHALLENGES

The following is a summary-level description of the major challenges facing technology and disposal site evaluation and selection.

Primary Wasteform Compliance with Disposal Criteria

Disposal criteria are critical in wasteform technology selection. The PA for onsite disposal evaluates vitrified LAW, including SLAW. The PA has not assessed grouted and steam-reformed primary wasteforms. Disposal of vitrified SLAW onsite at Hanford is the “baseline” case. It is noted that similar waste at the Savannah River Site is disposed of as a grouted wasteform in engineered disposal units. Also, out-of-state waste disposal sites with defined WAC are available. Criteria for disposal of radioactive and hazardous waste at sites outside the State of Washington are set by the states in which they are located.

Secondary Waste Disposal

Current planning assumes all WTP and SLAW solid secondary waste will be disposed of as a grouted wasteform at Hanford. Disposal of secondary waste immobilized in grout is not yet approved for onsite disposal. Secondary wastes include solid wastes, such as air filters, and liquid wastes generated during processing of primary wasteforms. Vitrification produces the secondary waste with the largest volume and highest curie content, which is evaluated as the dominant contributor to onsite disposal releases when vitrification is the primary wasteform.

Supplemental LAW Feed Uncertainties

SLAW content, volume, and feed rate assumptions are based on Hanford System Plan 8. System Plan 8 uses models based on best available data from the history of waste tank contents to calculate the anticipated feed flows as well as the radionuclides and other constituents that must be treated to comply with RCRA LDRs. The fidelity of this input data is uncertain, and the FFRDC team did not attempt to validate the System Plan 8 assumptions. In addition, tank waste processing per System Plan 8 is highly integrated, with many interdependencies between processes. Variability in tank waste removal, WTP pretreatment, and HLW processing rates and sequencing can impact SLAW input flowrates, compositions, and treatment processing demands.

Technical Maturity for SLAW Application

Vitrification is the current baseline technology for treating Hanford LAW/SLAW and is therefore the most technically mature for SLAW feed. Grouting has been used to immobilize low level radioactive liquid waste at the Savannah River Site (SRS) and many other facilities. However, it has not been fully demonstrated for immobilization of Hanford SLAW. Additional research and development (R&D) to demonstrate its acceptable wasteform performance for this application will be needed. Steam reforming is planned to immobilize the sodium-bearing waste (SBW) in the Idaho National Laboratory (INL) Integrated Waste Treatment Unit (IWTU), but steam reforming is the least technically mature for SLAW feed. The overall process will need to be matured for application to Hanford SLAW.

Significant Funding Needs

Regardless of technology, a SLAW treatment facility will be a significant capital project. Per System Plan 8, SLAW development, design, and construction will be coincident with completion of the WTP Pretreatment and HLW facilities, tank farm capital upgrades, and Direct Feed Low Activity Waste (DFLAW) operations. These projects will be competing for the funding (currently approximately $1.5B per year) managed by the Department of Energy's Office of River Protection (DOE-ORP) during SLAW construction and startup. This is in addition to tank farm operations, tank retrieval and closure, and completion/start-up of DFLAW. Independent of SLAW technology selection and project execution, annual projections for the above projects and operations in some years exceed 2X the current funding. This is a significant programmatic risk to integrated program success. There is a risk applicable to any selected processing technology that lack of funding appropriations could extend overall waste tank storage durations, thus extending and increasing tank storage risk. Figure 1 shows the challenge of "stacked costs" graphically, using SLAW vitrification as an example. The SLAW treatment costs are shown added to the other project and operating costs assumed by System Plan 8. The FFRDC team did not evaluate the System Plan 8 assumptions for any facility or operation other than Supplemental LAW.

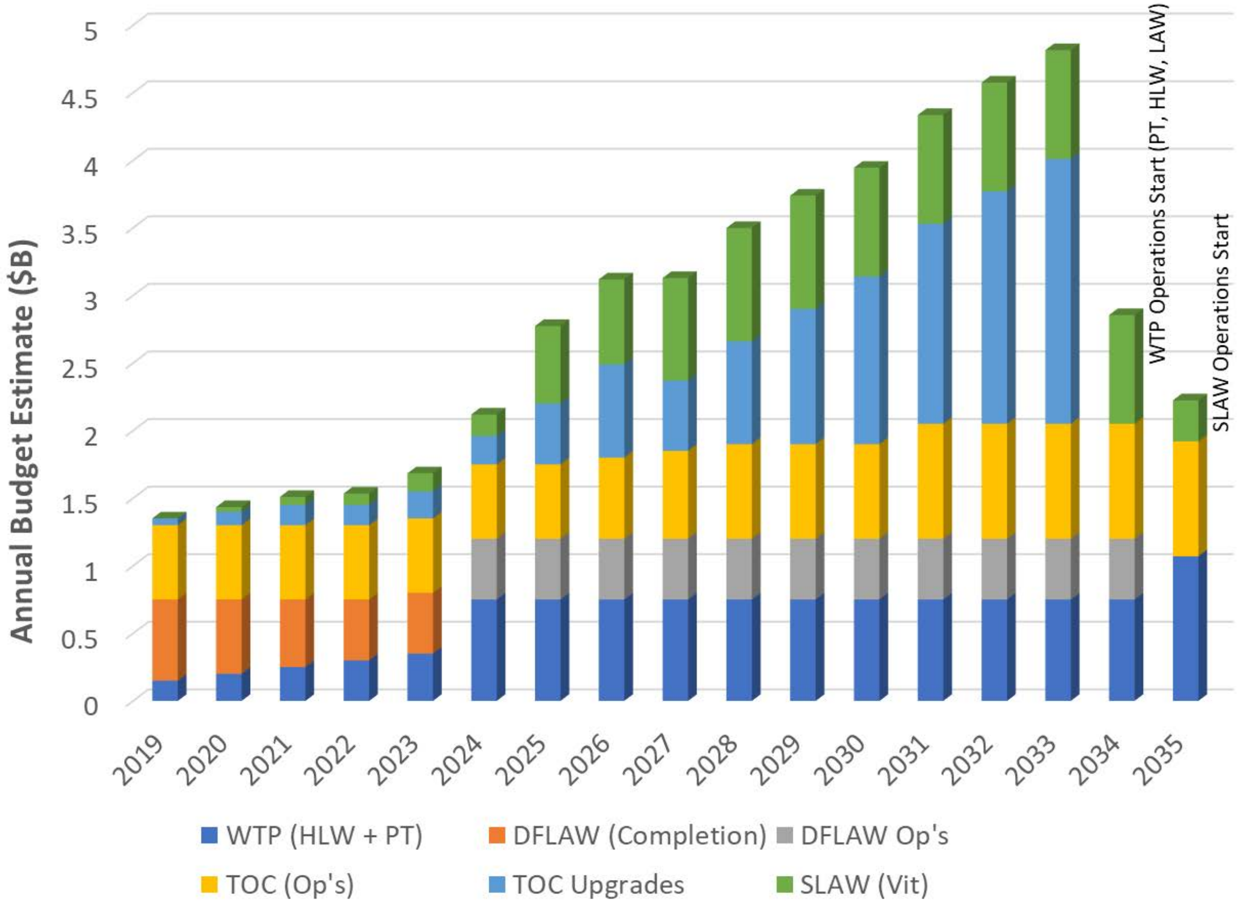

Figure 1 Budget for SLAW Vitrification in Conjunction with Key Hanford Mission Facilities and Operations

The following assumptions are made for this budget representation:

- Facility Operation (rad-ops) start dates (all facilities) match System Plan 8 Baseline Case.
- Ongoing WTP projects–HLW, DFLAW, Pretreatment (PT)–are flat funded at ≈$750M per year; this is slightly more than the current level (≈$690M per year). This implies combined HLW/PT to-go costs equate to ≈$9.5B (depending on ramp rate as DFLAW startup is completed). These values are not verified and are for reference only. It is noted the 2019 Hanford Lifecycle, Scope, Schedule and Cost report provides an estimated (low-end) HLW/PT to go-cost of $15.3B.
- Tank Operations Contract estimates are interpolated from System Plan 8, Baseline Case, except Supplemental LAW.
- Schedule requirements mandate significant total funding increases starting in or around 2024 and annual increases of ≈$250M through 2033.
- Supplemental LAW Vitrification is reflected using the low range costs for Total Project Cost and annual operations per this study. Flat funding ceiling of $750M annual assumed for the SLAW capital project.
- Costs for DOE Richland (RL) are not reflected. DOE-RL is currently a separate line item and does not impact DOE-ORP projections.
- Costs for Single-Shell Tank retrieval operations are intermittent, reflecting the current double-shell tank space limitations through HLW/PT operations, and are not included.
- SLAW costs are not escalated.

Schedule Urgency

Assuming a required HLW waste treatment completion date of 2063 and a typical capital project timeline, near-term decisions are needed for the SLAW treatment technology.

Emergent Studies and Future Scenarios

Over the years, numerous alternative concepts for tank waste processing at Hanford have been proposed in various levels of detail, which, if adopted, could impact the SLAW assumptions used to perform this analysis. Examples include:

- Direct Feed HLW
- At-Tank Treatment Alternatives
- HLW Definition Clarifications
- Improved LAW glass or process models.

Any of these examples would result in direct or indirect impacts on the assumptions in this analysis. It is not possible in this study to evaluate each potential future scenario as many of the scenarios have not been sufficiently defined to allow a definitive impact evaluation. If these scenarios progress, the impact on the SLAW mission needs to be considered.

Results of this study are generally unaffected by reports that have emerged since issuance of the NDAA17. In some cases, considerations such as out-year cost liabilities may not be quantitatively consistent with recent reports, but those emergent reports have not presented information that would alter the general results of this study.

COMPARISON TO THE ENVIRONMENTAL IMPACT STATEMENT

The most recent Hanford Environmental Impact Statement (EIS) concludes that the cost of grouting and steam reforming would be similar to the cost of vitrification but that the grouted and steam-reformed wasteforms would not comply with performance criteria for onsite disposal. This FFRDC analysis has drawn different conclusions related to cost and performance. Specifically, the FFRDC analysis found that the grouting and steam-reforming options would cost less than vitrification and that both would likely comply with criteria for onsite disposal. Appendix H provides discussion of key differences between the EIS and this analysis.

COMPARITIVE ANALYSIS

Table 2 presents a high-level comparative analysis of the three technologies against the criteria specified in NDAA17. A more detailed table is included in Section 4.0. Cost and schedule differences for the various disposal site options are covered within the cost and schedule ranges presented.

Table 2 High-level comparison of the three immobilization technologies per the analysis criteria specified in NDAA17

IMMOBILIZATION TECHNOLOGY	RISKS/ OBSTACLES*	BENEFITS	COSTS**	SCHEDULES***	ONSITE REGULATORY COMPLIANCE	OUT-OF-STATE REGULATORY COMPLIANCE
VITRIFICATION	• Most complex process • Most dependent on integrated facility performance o Highest throughput risk o Most impacted by feed rate variability o Lowest single-pass retention • Highest volume and curies secondary waste	• Most technically mature for SLAW feed • High temperature LDR organic/ nitrate destruction • Lowest volume primary waste	Highest: ~$20 to ~$36B	10-15 years	• Primary wasteform meets DOE Technical Performance Criteria (TPC) • Primary wasteform meets state permit requirements • May require mitigation for Iodine-129 in secondary waste	• Primary wasteform not evaluated • Secondary wastes meet WAC requirements
GROUTING	• LDR organics likely to require mitigation measures such as waste pretreatment or System Plan feed adjustments • May require Tc treatment for onsite disposal • Highest volume primary waste	• Least complex process • Least dependent on integrated facility performance o Lowest throughput risk o Greatest stop/start flexibility • Room-temperature process • Lowest volume and curies secondary waste	Lowest: ~$2B to ~$8B	8–13 years	• Primary wasteform likely to meet DOE TPC • Further validation of acceptable wasteform performance needed • May require mitigation for I-129	• Meets WAC (assuming LDR organics addressed) and transportation requirements
STEAM REFORMING	• Least technically mature for SLAW feed • Complex process • Requires rigorous process monitoring and control of fluidized bed and solids handling systems	• Lowest cost high temperature LDR organic/ nitrate destruction • Little waste volume increase during treatment • No liquid secondary waste	Middle-range: ~$6B to ~$17B	10-15 Years	• Monolithic primary wasteform likely to meet DOE TPC • Primary wasteform likely to meet state permit requirements • Further validation of acceptable wasteform performance needed • May require mitigation for I-129 in secondary waste	• Meets WAC and transportation requirements

**All technologies require significant concurrent Line Item and operations funding (>$1.5B/year).*

***Lifecycle costs are shown. SLAW capital expenses will occur at the same time as other WTP and Tank Operations Contract capital projects such that the overall projected costs of all concurrent projects and operations will be greater than 2 times the current $1.5B/year regardless of SLAW costs. This is a cross-cutting programmatic risk.*

****The times required to complete construction and startup of the facilities are shown. The window to startup of any Hanford SLAW immobilization facility is 15 years (to 2034).*

CONCLUSIONS

The following conclusions resulted from the FFRDC analysis of the SLAW treatment technologies:

- A viable SLAW treatment and disposal option can be developed for each of the three technologies evaluated (vitrification, grouting, and steam reforming).
- For grouting, both onsite and out-of-state disposal will likely require treatment of select LDR organics if found in the waste, and R&D and/or additional flowsheet studies will be needed to define that LDR treatment.
- Technetium and iodine removal is not needed for out-of-state disposal of grouted or steam reformed wasteforms.
- Technetium and iodine removal is not needed for onsite disposal of grouted or steam reformed wasteforms, assuming high performing grouted and steam reformed wasteforms.
- Grouting and steam reforming offer significant cost benefits over vitrification.
- No technology was evaluated highest in all NDAA17 study criteria.
- Near-term decision on SLAW treatment technology is needed to meet DOE mission completion goals.
- Implementing any of the SLAW treatment technologies will exceed current funding levels when combined with required spending for all WTP and tank projects concurrent with SLAW treatment.

1.0 PARAMETERS OF THE ANALYSIS

1.1 NEED AND TASK

Per River Protection Project System Plan 8 (October 2017), Hanford waste processing is currently scheduled to complete in 2063. However, approximately 60% of the Low Activity Waste (LAW) presently in the Hanford storage tanks as well as the LAW that will be generated during operation of the Hanford Waste Treatment and Immobilization Plant (WTP) will exceed the processing capacity of the WTP. That portion of Hanford LAW will require treatment external but parallel to WTP operation.[1]

Section 3134 of the National Defense Authorization Act for Fiscal Year 2017 (NDAA17) stipulates that a Federally Funded Research and Development Center (FFRDC) team conduct an analysis of approaches for supplemental treatment of Low Activity Waste at the Department of Energy's Hanford Nuclear Reservation.[2] FFRDCs, such as the Department of Energy's (DOE's) national laboratories, are sponsored and funded by the United States Government to meet special long-term research or development needs that cannot be met effectively in-house or by contractors.[3] NDAA17 also requires a concurrent review of the FFRDC team's analysis by the National Academies of Science, Engineering, and Medicine.

A decision on the approach and technology for the treatment of SLAW at Hanford has not been made. The results of the FFRDC team's analysis described in this report are intended to assist decision-makers in selecting the best approach and technology for SLAW treatment at Hanford.

1.2 SCOPE

Section 3134 of NDAA17 directs the FFRDC team to analyze several approaches to SLAW at Hanford:

- Further processing of the Low Activity Waste to remove long-lived radioactive constituents, e.g., additional pretreatment
- Vitrification
- Grouting
- Steam reforming
- Other alternative approaches.

Section 3134 of NDAA17 further directs the FFRDC team to consider several factors in analyzing those approaches:

- Risks
- Benefits
- Costs
- Schedules
- Regulatory compliance
- Obstacles to implementation.

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[1] "River Protection Project System Plan." ORP-11242. Rev 8. 2017. U.S. Department of Energy Office of River Protection. Richland, Washington.

[2] "Analysis of Approaches for Supplemental Treatment of Low Activity Waste at Hanford Nuclear Reservation." Section 3134. January 4, 2016. National Defense Authorization Act for Fiscal Year 2017.

[3] "Federally Funded Research and Development Centers." 48 CFR 35.017. October 1, 2005. United States Code of Federal Regulations.

Sections 2.0, 3.0, and 4.0 of this report summarize how the FFRDC team used these factors to analyze the individual approaches to Hanford SLAW treatment as well as to compare the approaches.

1.3 TECHNICAL BASIS

Each of the three immobilization technologies specified in NDAA17—vitrification, grouting, and steam reforming--has been previously evaluated and some testing performed for the Hanford tank waste. Vitrification and grouting have been previously utilized at West Valley and the Savannah River Site, while steam reforming is currently being implemented for wastes at the Idaho National Laboratory. These technologies have been used for commercial treatment of radioactive wastes also elsewhere in the United States and worldwide. To determine the likely technical feasibility of each immobilization technology, the FFRDC team compared the known relevant attributes of the treatment technology to the Hanford SLAW feed vector.

The only identified documentation specifying the intended waste stream feed vector for the future process for treatment of Hanford SLAW is the One System River Protection Project Integrated Flowsheet.

The Integrated Flowsheet presents the most recently calculated material balance for the entire Hanford tank waste immobilization program. It calculates all process streams that will be generated during immobilization of Hanford tank wastes, including the retrieval processes in the Hanford tank farms, processing through pretreatment facilities, and final wasteform generation as well as secondary waste stream generation, treatment, and disposal.

Figure 2 is a simplified diagram showing the Hanford tank farm, Waste Treatment and Immobilization Plant (WTP) facilities, and other required facilities.

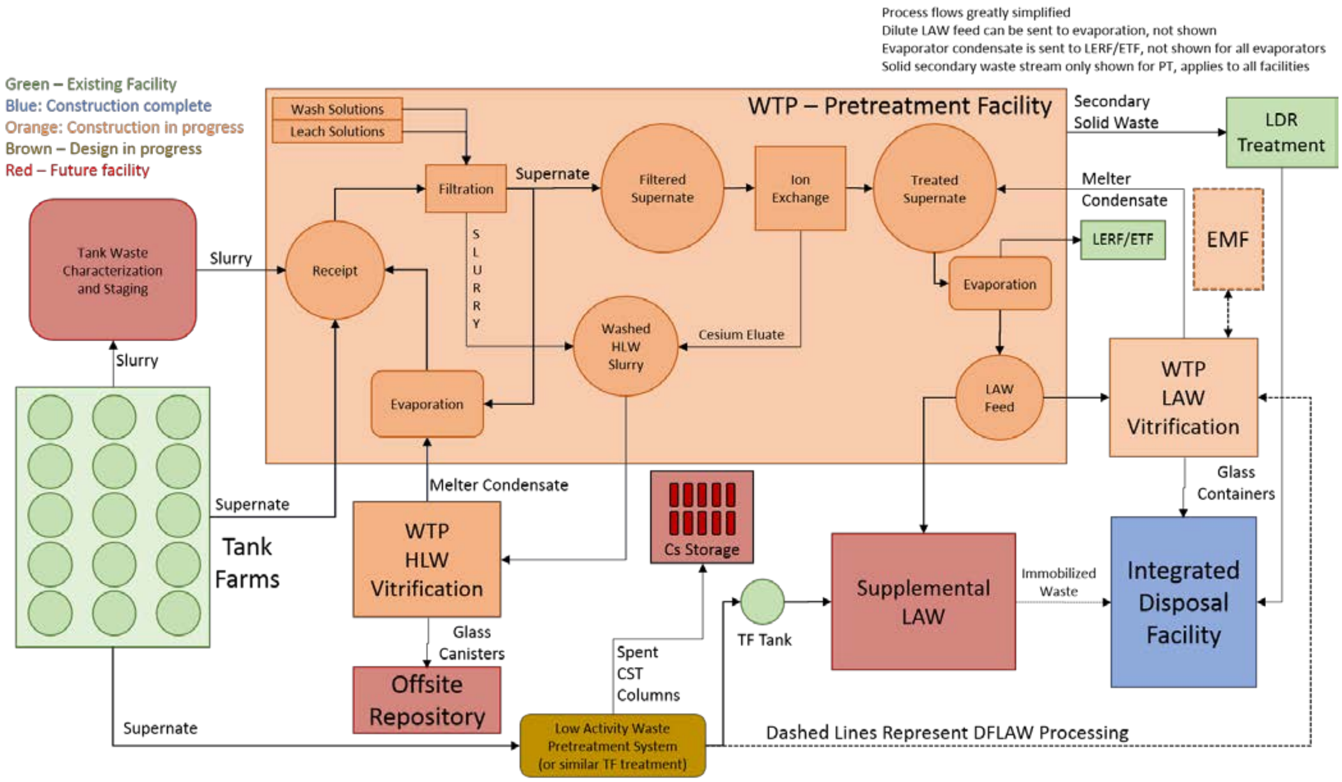

Figure 2 Simplified Flowsheet for Immobilization of Hanford Waste during Full WTP Operation

The SLAW facility is assumed to receive feed from the Low Activity Waste Pretreatment System (LAWPS) and the WTP Pretreatment (PT) facility, immobilize the LAW, package and ship the waste to a disposal facility, and internally handle any secondary wastes that require treatment prior to disposal. The feed vectors from LAWPS and PT are estimated by the Integrated Flowsheet.

Updated approximately every two years, the Integrated Flowsheet calculates the feed vector for SLAW from up-to-date information that includes the impact of new considerations regarding how the tank waste will be processed, such as inclusion of direct feed options or at-tank waste treatment that would generate treated LAW not bounded by the SLAW feed vector. See Appendix J, "Expanded Discussion: Feed Vector," for additional information about Hanford waste generation and processing and the SLAW feed vector.

The FFRDC team's analysis of the approaches to SLAW is based on the feed vector in the most recent version of the Integrated Flowsheet, Revision 2, issued in September 2017.[4] The Integrated Flowsheet, Revision 2, is based on assumptions contained in System Plan 8. The team did not attempt to validate System Plan 8 assumptions.

1.4 CHALLENGES TO HANFORD SLAW IMMOBILIZATION TECHNOLOGY EVALUATION AND SELECTION

In the course of its analysis, the FFRDC team identified major crosscutting challenges facing technology and disposal site evaluation and selection:

1. Primary Wasteform Compliance With Disposal Criteria
2. Secondary Waste Disposal
3. Supplemental LAW Feed Uncertainties
4. Technical Maturity for SLAW Application
5. Significant Funding Needs
6. Schedule Urgency
7. Emergent Studies and Future Scenarios

1. Primary Wasteform Compliance with Disposal Criteria

Onsite Disposal

In its Hanford SLAW analysis, the FFRDC team used the DOE-operated Integrated Disposal Facility (IDF) on the Hanford reservation as the "onsite" disposal facility. Located in the 200 East Area, the IDF is being authorized by DOE for disposal of the radioactive component of Hanford waste and by the State of Washington for disposal of the hazardous waste component (the DOE and the State have different authorities and different criteria).

A drinking water aquifer is approximately 300 feet below the landfill, and over long timeframes, surface water will travel to the water table.

The formal Performance Assessment (PA) for the Integrated Disposal Facility (IDF) was in progress but not finalized during the SLAW analysis, though the drafts provided to the FFRDC team were not expected to undergo major changes. Since the IDF radiological waste acceptance criteria (WAC) were not yet defined, the FFRDC team completed computer modeling to help determine whether treated SLAW would be acceptable for onsite disposal. The results of that performance evaluation are provided in Appendix F, "Disposal." The IDF is restricted from accepting wastes that do not meet Resource Conservation and Recovery Act (RCRA) Land Disposal Restriction (LDR) requirements.

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[4] L.W. Cree, J.M. Colby, M.S. Fountain, D.W. Nelson, V.C. Nguyen, K.A. Anderson, M.D. Britton, S. Paudel, and M.E. Stone, "One System River Protection Project Integrated Flowsheet, RPP-RPT-57991, Rev 2, 24590-WTP-RPT-MGT-14-023, Rev. 2," Washington River Protection Solutions (WRPS) One System, Richland, Washington, 2017.

Offsite Disposal

Several facilities outside the State of Washington may be viable for disposal of Hanford primary and secondary SLAW. For the purposes of the Hanford SLAW analysis, the FFRDC used Waste Control Specialists (WCS) in West Texas. WCS is a commercially-operated radioactive waste disposal facility licensed by the State of Texas. One of the WCS facilities is the Federal Waste Disposal Facility, which was designed, permitted, and constructed for disposal of Class A, B and C Low-level Waste (LLW) and Mixed Low-level Waste (MLLW) that is the responsibility of the Federal Government.

The WCS facilities are underlain by 600-foot (185-m) thick red-bed clays, and there is no drinking water aquifer beneath or adjacent to the WCS facilities. At WCS, wastes are emplaced 25 to 120 feet below the land surface in the disposal cell that includes a 7-foot thick multi-barrier liner.

WCS radiological WAC are well-defined; WCS is restricted from accepting wastes that do not meet LDR requirements.

2. Secondary Waste Disposal

The technology for SLAW immobilization has not been formally designated, but the Integrated Flowsheet assumes vitrification to be the baseline with grouting considered as an option. Secondary wastes include solid waste such as air filters and liquid wastes generated during processing of primary wasteforms. The current System Plan 8 assumption is that all solid secondary waste will be disposed of as a grouted wasteform at Hanford. Liquid secondary waste will first be sent to the Liquid Effluent Retention Facility-Effluent Treatment Facility (LERF-ETF). The contaminants removed from the liquid secondary wastes at LERF-ETF also will be grouted and disposed of onsite. The disposition of secondary waste from vitrification has been analyzed in the PA, but the permit for the IDF does not include the secondary wastes.

3. Supplemental LAW Feed Uncertainties

The composition of the feed vector from the Integrated Flowsheet has three major sources of uncertainty. First, the Best Basis Inventory (BBI) is the source of the tank compositions used to create the feed vector. The uncertainty in BBI data has been evaluated previously[5] as well as the impacts of a 20% variation for selected components on the baseline process[6]. The evaluation of uncertainty determined that 20% is not a bounding value, even for major analytes. In addition, specific data for organic species are not provided by the BBI to allow assessments of the need for treatment to destroy organic species prior to a grouting process. Selected RCRA metals, such as silver and barium, are considered supplemental analytes and data is available for only some of the wastes.

Second, the feed vector provided from the Integrated Flowsheet is based on proposed processing for retrievals and facility startup times that may change prior to SLAW startup. Retrieval and batch preparation experience at the Savannah River Site has shown that compositions of the tanks can be different than expected and that operational issues can lead to frequent departures from the planned retrieval sequence[7].

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[5] R.A. Peterson, “Transmittal of Summary for Waste-3 Best Basis Inventory Data Quality and Uncertainty Work Scope,” Pacific Northwest National Laboratory, Richland, Washington, LTR-EMSP-0105, 2016.

[6] J.D. Belsher, R.D. Adams, and K.L. Pierson, “Hanford Tank Waste Operations Simulator (HTWOS) Sensitivity Study,” Washington River Protection Solutions, Richland, Washington, RPP-RPT-51819, Rev 0, 2012.

[7] M.J. Cercy, D.K. Peeler, and M.E. Stone, “SRS Sludge Batch Qualification and Processing: Historical Perspective and Lessons Learned,” Savannah River National Laboratory, Aiken, South Carolina, SRNL-STI-2013-00585, 2013.

Third, the TOPSim model used to generate the feed vector has many simplifications[8]. These simplifications include, but are not limited to:

- Single parameter “split factors” to determine partitioning of most species through each unit operation including the melter and melter offgas system
- Lack of inclusion of the impact of melter idling on emissions from the melter
- SLAW modeled as a “black box”
- Line flushes in the WTP not included.

Thus, uncertainty in the compositions to be processed exists and could result in the feed vector from the Integrated Flowsheet being non-conservative for selected analytes. However, the feed vector is the best available information identified, and it is expected that a reasonable assessment of the viability of each technology can be ascertained from the use of the feed vector. The use of the maximum and minimum values versus an averaged value for the evaluations were used to provide an understanding of how components impact the immobilization technology.

The immobilization technologies have been previously evaluated over a wide range of compositions that may sufficiently cover the range of compositions expected from the Hanford SLAW feed vector. The evaluation of each immobilization technology case (and variants) considered the composition variation in the feed vector.

4. Technical Maturity for SLAW Application

Vitrification is the current baseline technology for treating Hanford LAW/SLAW and is considered the most technically mature for SLAW feed based on substantial testing at multiple scales with a range of LAW simulants; however, testing with actual radioactive LAW is limited to laboratory scale tests. Grouting has been used to immobilize low level radioactive liquid waste at the Savannah River Site (SRS) and many other facilities. However, it has not been fully demonstrated for immobilization of Hanford SLAW. Additional research and development (R&D) to demonstrate its acceptable wasteform performance for this application will be needed. Steam reforming is planned to immobilize the sodium-bearing waste (SBW) in the Idaho National Laboratory (INL) Integrated Waste Treatment Unit (IWTU), but steam reforming is the least technically mature for SLAW feed; the overall process will need to be matured for application to Hanford SLAW.

5. Significant Funding Needs

If additional pretreatment is necessary to make a technology viable for Hanford waste, it is noted that the pretreatment technologies could be at a lower technology readiness level than the immobilization technology. Schedule and cost estimates are challenging for technologies at lower readiness levels as any issues that arise during required technology development could significantly impact both.

Developing realistic cost estimates for each technology involves uncertainty and risk. It is noted that the initial estimates for some recent major line-item DOE projects (e.g., WTP at Hanford and the Mixed Oxide Fuel Fabrication Facility at the Savannah River Site) have been significantly exceeded during design and construction, illustrating the difficulty in accurate cost estimation. Because pre-conceptual designs are not developed for deployment of the technologies under review, comparisons to analog projects have been made based on the major unit operations needed. This methodology and the associated uncertainty is further discussed in Appendix J, “Cost Estimate Methodology and Basis.”

Regardless of technology, a SLAW treatment facility will be a significant capital project. Per System Plan 8, SLAW development, design, and construction will be coincident with completion of the WTP Pretreatment and HLW

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[8] A.M. Schubick, J.K. Bernards, N.M. Kirch, S.D. Reaksecker, E.B. West, L.M. Bergmann, and S.N. Tilanus, “Topsim V2.1 Model Requirements, RPP-RPT-59470, Rev 1.,” Washington River Protection Solutions, Richland, Washington, 2016.

facilities, tank farm capital upgrades, and Direct Feed Low Activity Waste (DFLAW) operations. Between now and 2034, these projects will be competing for the funding (currently approximately $1.5B annually) managed by the Department of Energy's Office of River Protection (DOE-ORP). This is in addition to tank farm operations, tank retrieval and closure, and completion/start-up of DFLAW.

Independent of SLAW technology selection and development/design/construction, annual projections for the above projects and operations exceed 2X the current funding. This is a significant challenge to integrated program success. There is a risk applicable to any selected processing technology that lack of funding appropriations could extend overall waste tank storage durations, thus extending and increasing tank storage risk. Figure 3 shows the challenge of "stacked costs" graphically, using SLAW vitrification as an example. It should be noted that the SLAW treatment costs are shown added to the other project and operating costs assumed by System Plan 8. The FFRDC team did not evaluate the System Plan 8 assumptions for any facility or operation other than Supplemental LAW.

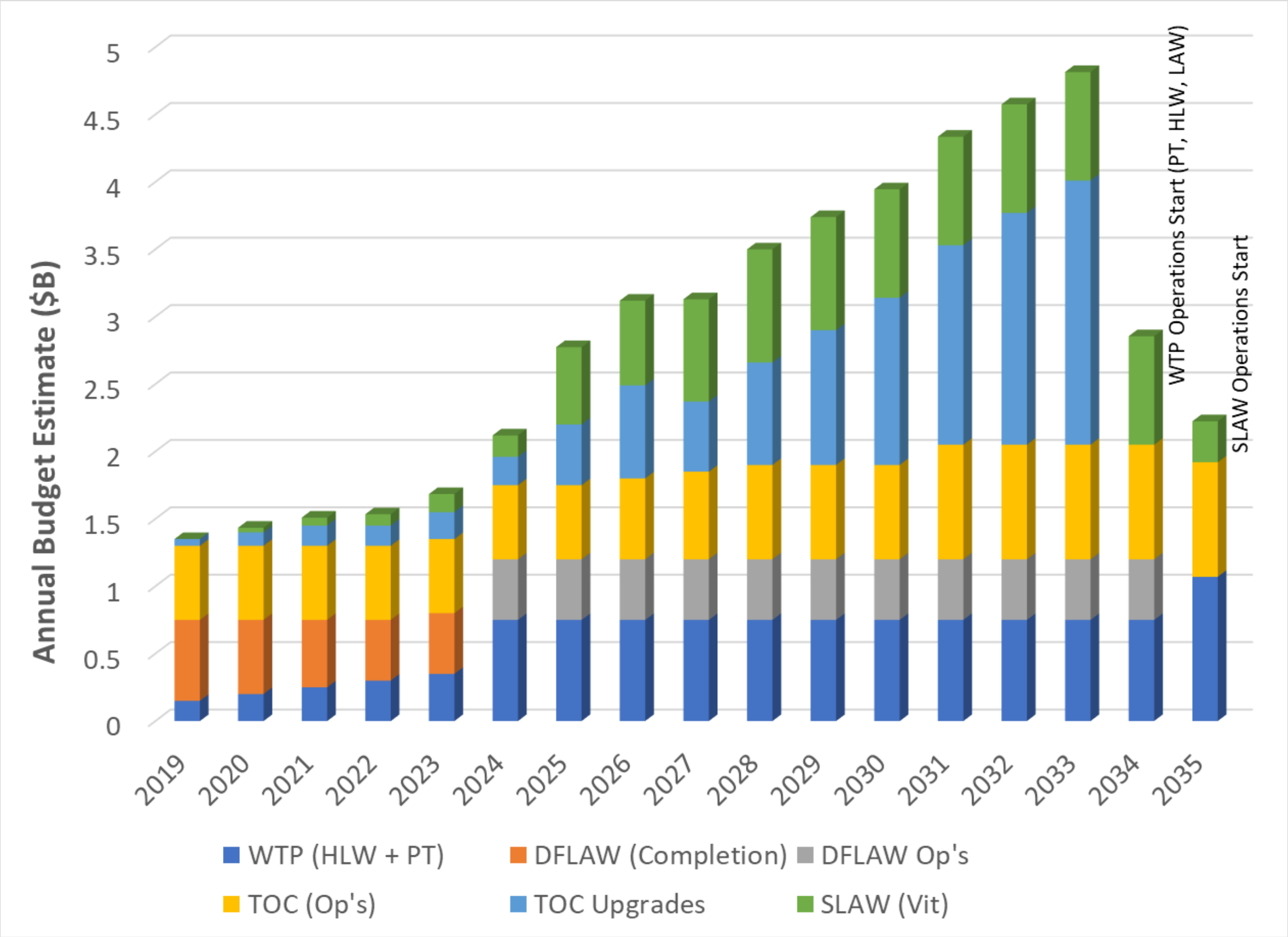

Figure 3 Budget for SLAW Vitrification in Conjunction with Key Hanford Mission Facilities and Operations

The following assumptions are made for this budget representation:

- Facility Operation (rad-ops) start dates (all facilities) match System Plan 8 Baseline Case.
- Ongoing WTP projects–HLW, DFLAW, Pretreatment (PT)–are flat funded at ≈$750M per year; this is slightly more than the current level (≈$690M). This implies combined HLW/PT to-go costs equate to ≈$9.5B (depending on ramp rate as DFLAW startup is completed). These values are not verified and are for

reference only. It is noted the 2019 Hanford Lifecycle, Scope, Schedule and Cost report provides an estimated (low-end) HLW/PT to go-cost of \$15.3B.[9]

- Tank Operations Contract estimates are interpolated from System Plan 8, Baseline Case, except Supplemental LAW.
- Schedule requirements mandate significant total funding increases starting in or around 2024 and annual increases of ≈\$250M through 2033.
- Supplemental LAW Vitrification is reflected using the low range costs for Total Project Cost and annual operations per this study. Flat funding ceiling of \$750M annual assumed for the SLAW capital project.
- Costs for DOE Richland (DOE-RL) are not reflected. DOE-RL is currently a separate line item and does not impact DOE-ORP projections.
- Costs for Single-Shell Tank retrieval operations are intermittent, reflecting the current double-shell tank space limitations through HLW/PT operations, and are not included.
- SLAW costs are not escalated.

6. Schedule Urgency

Assuming a required HLW waste treatment completion date of 2063 and a typical capital project timeline, near-term decisions are needed for the SLAW treatment technology. System Plan 8 assumes a startup date for SLAW treatment of 2034. For some options, the required time for construction and startup require an immediate start to allow completion by the required startup date.

7. Emergent Studies and Future Scenarios

Over the years, numerous alternative concepts for tank waste processing at Hanford have been proposed in various levels of detail, which, if adopted, could impact the SLAW assumptions used to perform this analysis. Examples include:

- Direct Feed HLW
- At-Tank Treatment Alternatives
- HLW Definition Clarifications
- Improved LAW glass or process models.

Any of these examples would result in direct or indirect impacts on the assumptions in this analysis. It is not possible in this study to evaluate each potential future scenario as many of the scenarios have not been sufficiently defined to allow a definitive impact evaluation. If these scenarios progress, the impact on the SLAW mission needs to be considered.

Results of this study are generally unaffected by reports that have emerged since issuance of the NDAA17. In some cases, considerations such as out-year cost liabilities may not be quantitatively consistent with recent reports, but those emergent reports have not presented information that would alter the general results of this study.

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[9] "2019 Hanford Lifecycle Scope, Schedule and Cost Report." January 2019. DOE/RL-2018-45. Revision 0. Richland Operations Office. Department of Energy. Richland, Washington.

2.0 CRITERIA FOR ANALYSIS OF TREATMENT APPROACHES

Section 3134 of NDAA17 requires that several factors be considered in the analysis of approaches for treating the portion of Hanford Low Activity Waste intended for supplemental treatment. Those factors are risks, benefits, costs, schedules, regulatory compliance, and obstacles to implementation.

The factors are not mutually exclusive. For example, costs, schedules, or regulatory compliance could constitute risks/obstacles to implementation or benefits.

This section describes how the FFRDC team defined and addressed each factor. How the factors were used in the analysis of each particular treatment option is summarized in Section 3.0 and is detailed in Appendices A-D.

Section 4.0 provides a high-level comparison of the primary treatment options in terms of those factors.

2.1 RISKS

The first analysis factor prescribed by Section 3134 of NDAA17 constitutes “the risks of the approaches…relating to treatment and final disposition.”

The FFRDC team considered a range of risks and candidate mitigation strategies.

The FFRDC team used a semi-quantitative methodology to characterize the risks associated with each of the SLAW cases. A full quantitative risk assessment was not feasible since design and operational specifics currently available would not support that depth of analysis.

The semi-quantitative approach adhered to a formal risk structure based on subject-matter-expert analysis of the following triplet:

1. Scenario: The combinations of events that would result in deviations from design/operational/programmatic intent
2. Probability: The likelihood of occurrence of each combination of events
3. Consequences: The impacts of each combination of events.[10]

The consequence metrics on which the study primarily focused were the incremental cost and the required extension in duration of the tank waste treatment mission associated with each scenario.

Following the analysis of the risks associated with the individual SLAW cases, the team performed a systematic risk-informed comparison among the options.

Discussion of Risk Assessment, including specific factors considered and comparative results, is provided in Appendix E.

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[10] The approach is similar to a family of semi-quantitative methods that include FMECA (failure modes, effects and criticality analysis), HAZOPS (hazard and operability studies), preliminary hazards analysis (PHA) and What-If? studies. [Guidelines for Hazard Evaluation Procedures, CCPS, Wiley, 2008].

2.2 BENEFITS

Section 3134 of NDAA17 requires analysis of “the benefits and costs of such approaches.” How the FFRDC team defined and addressed costs is summarized in Section 2.3.

In conjunction with the other criteria specified in the NDAA17 (costs, schedules, regulatory compliance) benefits or advantages of each approach to treating Hanford SLAW were assessed, including:

- Wasteform volume
  - Primary
  - Secondary
- Pretreatment requirements
- Ease of operation
- Flexibility.

The benefits of the individual treatment options are summarized in Section 3.0 and detailed in Appendices A-D.

2.3 COSTS

It is understood that lifecycle cost estimates are routinely updated to reflect best available forecasts. For example, information available to inform the Hanford Environmental Impact Statement (EIS)[11] in 2012 consistently provided WTP LAW Forecast at Completion costs of ≤ $1.7B. A current (2017) status per the United States Government Accountability Office (GAO) provides a WTP LAW completion estimate of $6.5B (potentially higher, depending on how DFLAW costs are apportioned), clearly demonstrating the project challenges and cost escalation.[12] This updated information was used by the FFRDC team to evaluate SLAW vitrification project costs and consider how a SLAW project would fit alongside completion of WTP PT and WTP HLW. SLAW vitrification cost estimates were generated using WTP LAW as an analog. Analog facilities also were used to generate the cost estimates for grouting and steam reforming.

Results of this study are generally unaffected by reports that have emerged since issuance of the NDAA17. In some cases, considerations such as out-year cost liabilities may not be quantitatively consistent with recent reports, but those emergent reports have not presented information that would alter the general results of this study.

Per System Plan 8, SLAW operations commence in 2034. It is assumed that funding will be made available starting in FY 2020. All Supplemental LAW options will comprise a capital project and be governed by DOE Order 413.3B, “Program and Project Management for the Acquisition of Capital Assets.”[13] As such, the expected capital project duration cannot be projected under ≈8 years based on historical and recent Complex experience. Recent project experience is consistent with longer durations. Additionally, project funding has often been “capped,” i.e., annual funding limited, independent of the project estimate. Annual budget estimates are consistent with this experience.

Currently, the top Hanford mission priority is startup of DFLAW. This project has both WTP (Effluent Management Facility evaporator, EMF) and Tank Operations Contract (Low Activity Waste Pre-treatment

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[11] “Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington.” DOE/EIS-0391. November 2012. U.S. Department of Energy.

[12] Bechtel National, Inc. Summary of May 2006 EAC to-Go Costs by Facility, as found in RPP-RPT-47908, Rev. A.

[13] “Program and Project Management for the Acquisition Of Capital Assets.” DOE Order 413.3B. Approved Nov 29, 2010. Updated Apr 12, 2018. U.S. Department of Energy. Washington, DC.

System, LAWPS) facilities and capabilities (waste feed delivery, etc.). Commencement of DFLAW hot operations is scheduled for 2021, with a compliance deadline of May 2023. WTP PT and WTP HLW will be the major WTP construction projects required prior to SLAW under the current mission scenario. Additional Hanford projects required in advance or at the same time of SLAW include (among others) the East Area Waste Retrieval Facility (WRF) and the Tank Waste Concentration and Storage (TWCS) capability/facility. Contact Handled Transuranic (CHTRU) waste recovery and packaging operations and sludge tank retrievals (possibly AN-103 and AN105) also will be performed concurrently.

SLAW technology development, pilot operations, and capital project will compete for priority and budget with DFLAW operations in addition to the above construction projects, startups, and Tank Operations Contract operations. The hot startup of SLAW in conjunction with the nominal duration of capital projects mandates no fewer than 6 years of overlap with WTP PT and WTP HLW and likely several of the other key facilities. Applying a flat funding scenario is consistent with this overlap, but the level of funding is defined by the projected cost (as a function of time).

Costs are full life-cycle costs, which include technology development, construction, operations, transport, and deactivation and decommissioning.

See full discussion of Cost Estimation Methodology and Results in Appendix H.

2.4 SCHEDULES

Section 3134 of NDAA17 also prescribes analysis of “anticipated schedules for such [treatment] approaches, including the time needed to complete necessary construction and to begin treatment operations.” Schedules were developed in conjunction with cost estimates for each case. The schedules reflect team experience in process development and recent DOE capital projects.

Per System Plan 8, the window to startup of any Hanford SLAW immobilization facility would be limited to 15 years; however, this was not used to constrain the high-end capital facility construction duration.

The schedules of the individual treatment options are summarized in Section 3.0 and detailed in Appendices A-D.

2.5 REGULATORY COMPLIANCE

Section 3134 of NDAA17 also prescribes analysis of “the compliance of such approaches with applicable technical standards associated with and contained in regulations prescribed pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (42 U.S.C. 9601 et seq.), the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.) (commonly referred to as the ‘‘Resource Conservation and Recovery Act of 1976’’), the Federal Water Pollution Control Act (33 U.S.C. 1251 et seq.) (commonly referred to as the ‘‘Clean Water Act’’), and the Clean Air Act (42 U.S.C. 7401 et seq.).”

The FFRDC team analyzed the regulatory compliance of the five Hanford SLAW immobilization cases with the federal acts specified in the NDAA17 as well as corresponding state laws and permitting requirements for disposal at the Hanford IDF and at WCS in Texas. Additional information on the disposal sites and analysis of the acceptability of each wasteform for these sites can be found in Appendix F.

In addition, based on the guidance provided in DOE Order 435.1, "Radioactive Waste Management",[14] the team identified additional regulations that might be applicable, such as:

- Occupational Radiation Protection requirements (10 CFR Part 835) for oversight of radioactive waste management facilities, operations, and activities;
- Toxic Substances Control Act (TSCA) requirements (40 CFR Part 761) for low-level waste containing polychlorinated biphenyls, asbestos, or other such regulated toxic components[15] (See Ref. 7); and
- As low as reasonably achievable (ALARA) exposure requirements under Radiation Protection of the Public and the Environment (10 CFR Part 834) and DOE 5400.5

Further, various transportation and packaging requirements were found to be applicable for onsite or out-of-state disposal of immobilized SLAW. Some applicable regulations include DOE Orders 435.1, 460.1A, and 460.2, and other Department of Transportation (DOT) requirements. Additional information on transportation of the treated waste to WCS can be found in Appendix G.

Integrated discussion of Regulatory Compliance can be found in Appendix I.

2.6 OBSTACLES TO IMPLEMENTATION

Finally, Section 3134 of NDAA17 prescribes analysis of "any obstacles that would inhibit the ability of the Department of Energy to pursue such approaches." The FFRDC team interpreted that to mean any obstacles not encompassed by the other factors. In most cases, risks and obstacles are combined into program risks/obstacles.

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[14] DOE Order 435.1 governs the management of radioactive waste at DOE sites, including criteria for wastes that are not considered high-level.

[15] Under DOE G 435.1-1 Section IV.B, TSCA-Regulated Waste is the low-level waste containing polychlorinated biphenyls, asbestos, or other such regulated toxic components, and shall be managed in accordance with requirements derived from the Toxic Substances Control Act, as amended, and DOE O 435.1.

3.0 SUMMARIES OF ANALYSES OF TREATMENT APPROACHES

Section 3134 of NDAA17 requires that the criteria described in Section 2.0 be used to analyze the following approaches for treating the portion of Hanford Low Activity Waste intended for supplemental treatment:

- Further processing of the Low Activity Waste to remove long-lived radioactive constituents
- Vitrification
- Grouting
- Steam reforming
- Other alternative approaches.

The three principal immobilization technologies are vitrification, grouting, and steam reforming. Further processing of the Low Activity Waste to remove long-lived radioactive constituents was analyzed by the team as a potentially necessary pretreatment step in achieving the immobilization end-states. The other alternative approaches identified by the team were judged not to outperform the specified technologies so were not analyzed to the same extent.

3.1 PRETREATMENT

Pretreatment beyond the removal of cesium and suspended solids specified in the baseline operations plan—which is applicable to all the cases considered—was assessed only for the grouting immobilization options. Some portion of the feed vector may require additional pretreatment to address LDR organics prior to grouting; however, the assessment also considered an alternative strategy to treat only LDR-organic-compliant SLAW by grouting and non-compliant SLAW by vitrification. The assessment also considered additional pretreatment to remove iodine (I), technetium (Tc), or LDR metals should that be needed to meet waste acceptance criteria for grout. (It should be noted that the assessment concluded there is a high likelihood that LDR metals will be handled well by grouting, such that pretreatment will be unnecessary; further, the assessment found that grout may or may not require additional pretreatment to address radionuclides to meet waste acceptance criteria. Finally, removal of Sr was identified as an opportunity that could reduce disposal costs at off-site facilities.

3.1.1 Requirements

3.1.1.1 LDR Organics

Significant characterization of radionuclides and inorganics in the liquid and solid phases of the tank waste has been conducted and is continuing; however, data on presence and concentration of LDR organics in the SLAW feed is still very limited. Hanford tanks are suspected of containing a wide range of LDR organics, as documented in the Part A RCRA Permit for both SSTs and DSTs. Establishing a firm removal requirement for either the LDR organics or metals is problematic based on the current level of underlying characterization of the feed vector. Total organic carbon is used in the BBI to show the amount of organic species present in the waste. Recent organics characterization of a very limited set of tank waste samples has identified some LDR organics, but most at very low levels, and this limited data cannot be extended to the broader set of tanks. There is, however, a more robust set of organics data from headspace and tank farm exhauster stack emissions sampling. This data can be used to estimate the maximum potential organic content in the tank liquid wastes by converting maximum tank headspace and exhauster measurements of all LDR organics actually detected in historic sampling to liquid waste concentrations using Henry's Law Constants for each organic. This approach should be considered a screening-level analysis, designed to assess whether there was a potential for LDR organics to exceed LDR total waste standards that could indicate pretreatment will be required. The results are shown in Table 3. Based on this approach:

- 114 relevant LDR organics are known or suspected to be present in the tank waste based on results of a regulatory data quality objectives process

- 61 of these LDR organics have been detected in tank headspace or tank farm exhausters above detection levels
- 22 of the LDR organics have the highest potential to exceed LDR total waste standards, based on approximate tank waste concentrations estimated from maximum vapor concentrations in one tanks.

The results shown in the third column ("Henry's Law: Exceedance of Total Waste Standard…") of Table 3 are not representative of any single tank but are an aggregate of the highest reported values across all tanks. A similar approach was taken for sampling data from a single tank, AW-106. Only N-methyl-N-nitroso methanamine, (CAS#62-75-9) exceeded the Total Waste Standard for the AW-106 sample. It is worth noting that in many cases, the analytical reporting limit itself was higher than the LDR standard.

Table 3 Potential LDR Organic in Exceedance of Total Waste Standard

		Henry's Law	**AW-106 R**
Chemical Name	**CAS Number**	**Exceedance of Total Waste Standard (from Max Headspace Vapor Conc.) (Cmax / Cstd)**	**Exceedance of Total Waste Standard (Cmax / Cstd)**
Propane, 2-nitro-	79-46-9	N/A[16]	
Phenol	108-95-2	2060	0.000
1,2-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	117-81-7	1140	0.000
Ethanone, 1-phenyl-	98-86-2	687	0.000
Phenol, 2-methyl-	95-48-7	483	0.000
1,2-Benzenedicarboxylic acid, diethyl ester	84-66-2	235	0.000
Morpholine, N-nitroso-	59-89-2	137	0.000
2-Propanone	67-64-1	126	0.105
Methanamine, N-methyl-N-nitroso-	62-75-9	113	**4.530**
2-Butanone	78-93-3	104	0.035
1-Butanol	71-36-3	95.9	0.000
Pyridine	110-86-1	75.5	0.000
Methanol	67-56-1	49.1	0.000
Acetic acid ethyl ester	141-78-6	40.4	0.000
Propanenitrile	107-12-0	34.1	0.000
Acetonitrile	75-05-8	7.6	0.000
1-Propanol, 2-methyl-	78-83-1	5.5	0.000
Dichloromethane	75-09-2	5.1	0.000
2-Pentanone, 4-methyl-	108-10-1	4.9	0.000
9H-Fluorene	86-73-7	2.1	0.000
2-Propenal	107-02-8	1.5	0.000
1-Propanamine, N-nitroso-N-propyl	621-64-7	1.5	0.000

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[16] 2-nitro-propane has treatment-based standard rather than concentration-based standard

Based on this screening approach, prudent planning would assume that for at least some portion of the feed vector, pretreatment would be required to reduce the organic content if the immobilization process does not destroy organic species. The extent of removal required is 50 to 99.9% based on the maximum detected values from the vapor space analysis.

3.1.1.2 LDR Metals

For the RCRA listed metals, some (e.g., silver and barium) are supplemental analytes in the BBI, and information on amounts of these metals in the waste is not available for all tanks. Like organic treatment, it is prudent to assess removal of RCRA metals from the feed stream or complexation within the wasteform for selected wasteforms.

3.1.1.3 Technetium

The removal of Tc is part of a potential mitigation strategy to be employed as needed to ensure that the SLAW grout meets the onsite disposal performance goals. The basis for the Tc removal is the 2017 Integrated Disposal Facility (IDF) Performance Assessment (PA). The underlying assumptions are that:

- Liquid Secondary Waste (LSW) grout is conservative relative to performance of a grouted SLAW wasteform.
- SW performance extrapolation is linear to much higher Tc inventories.
- Fraction split of Tc inventory between LAW and SLAW is 50%.

Based on these assumptions and a maximum groundwater limit of 900 pCi/l to meet regulatory requirements[17], an overall Tc removal of ~92.2% would be required for a grouted wasteform. To limit the groundwater concentration to 100 pCi/l, an overall Tc removal of ~99% would be required. It should be noted that these values are based on early assessment of the potential need for pretreatment and are not reflective of the performance shown in the PE conducted as part of the FFRDC review. The PE has shown that Tc removal is not required to meet requirements for high performance grouts. See Appendix F, “Disposal.”

3.1.1.4 Iodine

The basis for the iodine (I) removal is the 2017 IDF PA and was determined in a similar manner. It was assumed that the fraction of I inventory in to be sent to SLAW is 50% of that to be sent to WTP LAW.

Based on these assumptions and a maximum groundwater limit of 1 pCi/l to meet regulatory requirement[18], an overall iodine removal of ~50% would be required for a low performing grouted wasteform. To limit the groundwater concentration to 0.05 pCi/l, an overall I removal of ~97% would be required. It should be noted that these values are based on early assessment of the potential need for pretreatment and are not reflective of the performance shown in the PE conducted as part of the FFRDC review. The PE has shown that I removal is not required to meet requirements for high performance grouts. See Appendix F, “Disposal.”

3.1.1.5 Strontium

The removal requirements for Sr, if determined to be needed to support the Grouting Case II Opportunity variant that would change the classification of the resulting waste, are based on providing a significant degree of waste reclassification to justify the additional processing cost. Data on the feed vector was available on a monthly basis and was analyzed in that form (additional data on the feed vector is presented in appendix L). Grouting the baseline feed vector with no Sr removal will result in the waste being classified as Class C for 33 of the 441 months of processing with the balance being classified as Class B. The TRU content of the Feed Vector during those 33 of the months is the driving factor resulting in the classification as Class C waste. Removal of

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[17] 40 CFR 141, National Primary Drinking Water Regulations

[18] 40 CFR 141, National Primary Drinking Water Regulations)

90% to 95% Sr from the waste stream reduces the amount of Class B waste produced by only 17 to 23%, respectively, with 70 to 94 months, respectively, becoming Class A waste. However, with 99% Sr removal 406 of the 408 months in with the grouted waste would have been categized as Class B waste could be classified as to Class A.

It is possible that the amount of strontium removal required could be less than assumed; however, it is likely the amount of soluble Sr-90 would still require some treatment to allow the waste to meet Class A requirements.

It is noted that the ion exchange resin for cesium removal during DFLAW has been changed from spherical resourcinol-formaldehyde (sRF), an elutable resin, to Crystalline Silico-titanate (CST), a non-elutable resin.[19] CST will sorb soluble Sr; additional research is required to better understand the amount of Sr removal expected. Thus, the need for Sr removal could be decreased by the changes to the cesium removal process during DFLAW.

3.1.2 Selected Pretreatment Technologies

For many of these species, multiple pretreatment technologies have been studied to various degrees. This section will highlight only the selected pretreatment technologies. Additional information on selected alternative technologies and additional details on the technologies discussed below can be found in Appendix A, "Pretreatment."

3.1.2.1 LDR Organics

For this application, relatively low temperature oxidation is proposed. The addition of permanganate is proposed as a primary means, and ozone is proposed if additional oxidation is required. Care must be taken relative to the addition of excess permanganate if subsequent processing steps require the use of chemical reductants to be effective. One obvious advantage to the use of ozone is that it does not add to the volume of the waste stream.

The team reviewed the available literature regarding the reactivity of the 22 LDR organic compounds identified by the scoping analysis. It should be noted that data on the effectiveness of chemical oxidation with either permanganate or ozone were not found for all the potential compounds requiring treatment. Fifteen of these compounds will be at least partially oxidized by ozone or permanganate. However, partial oxidation, such as the conversion of alcohols or aldehydes to carboxylic acids, will not necessarily reduce the concentration below actionable levels. Of the seven remaining LDR organic compounds, six compounds–Acetonitrile, Dichloromethane, 2-Propanone, Pyridine, 2-nitro-propane, and 2-butanone–are not expected to react with permanganate or ozone, based on the literature (see Appendix A). No references were found for the oxidation of Propanenitrile with either permanganate or ozone; however, this compound is not expected to be reactive like acetonitrile.

Additional R&D will be required to evaluate the effectiveness of organic treatment where data is not available and to confirm the effectiveness at the expected levels and chemical matrix. It is anticipated that there will be some cases where the chemical oxidation will not be effective or effective enough. In these cases, a potential mitigation option would be to preferentially treat problematic organic bearing tanks via WTP LAW vitrification.

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[19] Oji, L.N.; Martin, K.B.; Hobbs, D.T. "Selective Removal of Strontium and Cesium from Simulated Waste Solution with Titanate Ion-exchangers in a Filter Cartridge Configurations-1209 ." SRNL-STI-2011-00697. February 26, 2012. Savannah River National Laboratory. Aiken, SC.

3.1.2.2 LDR Metals

Sulfide precipitation with Na_2S is highly effective in achieving a high degree of separation of heavy metal cations (Cd, Zn, Cu, and Pb) and of the oxyanions of arsenic and selenium from complex wastewaters. These separations were evaluated with a dilute synthetic mixture and with actual copper smelting plant wastewater. They were able to achieve removals of Cd, Zn, and Cu from the actual wastewaters of greater than 99%, and As and Se removals of 98 and >92%, respectively. Cd, Cu, and Zn concentrations in the range of 0.05 to 0.1 mg/1 were achieved with sulfide precipitation. The use of sulfide precipitation resulted in metal separations and settling rates considerably higher than those obtained with conventional hydroxide precipitation (lime).[20]

3.1.2.3 Technetium

Technetium-99 is, in most cases, present in the supernatant liquid as the pertechnetate ion (TcO_4^-). It is possible to remove this radionuclide through a number of processes, such as ion exchange, solvent extraction, crystallization, or precipitation. DOE conducted extensive testing of commercial and developmental ion-exchange materials in the early 1990's to determine suitable materials for separating various radionuclides from Hanford Site tank waste solutions. (SuperLig® 639 resin was not being manufactured at the time the TWRS program conducted these tests.)[21]

Tests conducted using SuperLig® 639 ion exchange resin on two tank-waste supernates exhibited a high fraction of nonextractable technetium (nonpertechnetate): AN-102/C-104 was 50% nonpertechnetate, and AP-104 was 69% nonpertechnetate. The pertechnetate removal for all tested supernates, showed an average of 99% removal for supernates that were essentially all pertechnetate and 86% removal for supernates that contained a high fraction of nonpertechnetate.[22] A 2002 report recommended that technetium be removed from the dissolved saltcake waste using SuperLig 639 resin.[23]

The WTP project conducted extensive testing of SuperLig® 639 in the late 1990s and 2000s. Chemical and radiation stability testing of SuperLig® 639 resin has also been conducted and a preliminary ion-exchange model developed. Technetium removal was included in the initial WTP design but subsequently dropped.

3.1.2.4 Iodine

Iodine removal from tank waste supernates has not been evaluated to the extent of other radionuclides. Selected laboratory studies were found using silver absorbents, but these studies represent work at very low TRL levels.

Some very recent work on the removal of radioactive iodine from alkaline solutions containing fission products using an alumina doped material containing silver nanoparticles (Ag NPs.) achieved iodine removal and recovery efficiencies of 99.7%.[24]

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[20] D. Bhattacharyya, A. B. Jumawan Jr. & R. B. Grieves (2006) Separation of Toxic Heavy Metals by Sulfide Precipitation, Separation Science and Technology, 14:5, 441-452, DOI: 10.1080/01496397908058096.

[21] William R. Wilmarth , Gregg J. Lumetta , Michael E. Johnson , Michael R. Poirier , Major C. Thompson , Patricia C. Suggs & Nicholas P. Machara (2011) Review: Waste-Pretreatment Technologies for Remediation of Legacy Defense Nuclear Wastes, Solvent Extraction and Ion Exchange, 29:1, 1-48, DOI: 10.1080/07366299.2011.539134

[22] E. Burgeson , J. R. Deschane & D. L. Blanchard Jr. (2005) Removal of Technetium from Hanford Tank Waste Supernates, Separation Science and Technology, 40:1-3, 201-223, DOI: 10.1081/SS-200041916.

[23] K. A. Gasper, K. D. Boomer, M. E. Johnson, G. W. Reddick, Jr., A. F. Choho, J. S. Garfield, (2002) Recommendation for Supplemental Technologies for Potential Mission Acceleration, CH2MHill Hanford Group, Inc., RPP-11261 Revision 0, July 2002

[24] Taewoon Kim, Seung-Kon Lee, Suseung Lee, Jun Sig Lee, Sang Wook Kim, Development of silver nanoparticle–doped adsorbents for the separation and recovery of radioactive iodine from alkaline solutions, Applied Radiation and Isotopes 129 (2017) 215–221, http://dx.doi.org/10.1016/j.apradiso.2017.07.033.

Laboratory tests also have been conducted recently by Asmussen et al.[25], using several Ag-containing materials as immobilization agents, or "getters", for iodine removal from deionized (DI) water and a liquid Hansford LAW simulant. These getter materials included Ag impregnated activate carbon (Ag–C), Ag exchanged zeolite (Ag–Z), and argentite. In the anoxic batch experiments with LAW simulant, Ag–Z vastly outperformed the other getters with Kd values of 2.2×10^4 mL/g at 2 h, which held steady until 15 days, compared with 1.8×10^3 mL/g reached at 15 days by the argentite. Asmussen et al.[26], also conducted batch sorption experiments using silver-functionalized silica aerogels remove iodine from both deionized water (DIW) and various Hanford Site Waste Treatment Plant (WTP) off-gas condensate simulants. These batch tests ran for periods as long as 10 days and were challenged with iodine concentrations of 5 to 10 ppm as iodide (I^-) or iodate (IO_3^-). They found in batch test that for neutral, less-complex systems, the sorbent rapidly removed the I^- from the solution and showed preferential removal of I^- over Br^- and Cl^-. They also showed that the silver-functionalized silica aerogels were able to remove IO_3^- but at a slower rate than for I^-.

If iodine removal is determined to be required, extensive R&D will be required to develop and mature the technology needed.

3.1.2.5 Strontium

MST was developed at Sandia National Laboratory (SNL) in the 1970's as an inorganic sorbent material that exhibits high selectivity for strontium and actinide elements in the presence of strongly alkaline and high-sodium salt solutions. The Savannah River Site selected this material for ^{90}Sr and plutonium removal from HLW solutions in the early 1980s as part of what was referred to as the In-Tank Precipitation (ITP) process.[27] In 2001, DOE selected MST for the strontium/actinide separation step within the Salt Waste Processing Facility (SWPF). Subsequently, MST was selected for use in the Actinide Removal Process (ARP) to treat waste solutions low in cesium activity. Strontium removal is very rapid, whereas sorption of the plutonium and neptunium occurs at slower rates from the strongly alkaline and high-ionic-strength waste solutions.

MST has been successfully deployed in the ARP at the Savannah River Site. Recent results from SRNL on a modified version of monosodium titanate show promise to reduce contact times for the strontium and TRU removal.

A Technology Readiness Assessment Report was prepared in 2009 to examine the Salt Waste Processing Facility at the Savannah River Site. This assessment included the Alpha Strike Process where the SWPF feed is chemically adjusted and MST added as well as the subsequent cross-flow filtration unit. The MST adsorbs the Sr and actinides, and the resulting MST slurry is filtered to produce a concentrated MST/sludge slurry and a Clarified Salt Solution (CSS) filtrate. The concentrated MST/sludge slurry is washed to reduce the sodium ion (Na^+) concentration and transferred to the DWPF for vitrification while the CSS is routed to the CSSX process. The Feed Adjustment System was determined to be TRL 6 because of the range of laboratory- and bench-scale tests with actual waste and particularly by the large-scale equipment tests that involved batches of SWPF feed simulant. The cross-flow filter system was also evaluated and determined to be at TRL 6.[28] Laboratory scale tests

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[25] Asmussen, R. M., J.J. Neeway, A.R. Lawter, A. Wilson, N. Qafoku, Silver based getters for 129-I removal from low activity waste, Radiochim Acta 104 (12) (2016) 905–913, DOI 10.1515/ract-2016-2598.

[26] Asmussen, R.Matthew., Josef Matyáš, Nikolla P. Qafoku, Albert A. Kruger, Silver-functionalized silica aerogels and their application in the removal of iodine from aqueous environments, Journal of Hazardous Materials (2018), https://doi.org/10.1016/j.jhazmat.2018.04.081.

[27] William R. Wilmarth , Gregg J. Lumetta , Michael E. Johnson , Michael R. Poirier , Major C. Thompson , Patricia C. Suggs & Nicholas P. Machara (2011) Review: Waste-Pretreatment Technologies for Remediation of Legacy Defense Nuclear Wastes, Solvent Extraction and Ion Exchange, 29:1, 1-48, DOI: 10.1080/07366299.2011.539134

[28] Kurt D. Gerdes, Harry D. Harmon, Herbert G. Sutter, Major C. Thompson, John R. Shultz, Sahid C. Smith, "Savannah River

with real wastes and full-scale tests with a range of simulants using prototypical equipment have been completed.

Finally, it is noted that a process has been developed and is planned for use in the tank farms to reduce soluble Sr and TRU from tanks AN-102 and AN-107. This process will add strontium nitrate to the tank to force most of the Sr-90 to precipitate along with the stable Sr. The concentration of total strontium in the supernate is increased, but the amount of Sr-90 is decreased by isotopic dilution. This process will be followed by a sodium permanganate strike to precipitate TRU species. System Plan 8 and the feed vector from the Integrated Flowsheet already account for these processes for these tanks.

3.1.3 Approach To Pretreatment

The conceptual flowsheet for the two grouting cases is shown in Figure 4. This is a relatively simple system for the chemical oxidation of the LDR organic, if required. The feed enters one of two feed tanks that are used for chemical analysis to determine the extent of pretreatment required. If LRD organic removal is required, this will also be accomplished in this tank with the addition of a sodium permanganate strike and / or the use of ozone. The permanganate strike would also be expected to precipitate and remove much of the soluble TRU components from the waste feed. The contents of the vessel are then analyzed again to verity the effectiveness of the oxidation step prior to its transfer to the SLAW immobilization step.

In addition to the base grouting cases evaluated, analysis of the risks and opportunities indicated that in some cases, the level of Tc and iodine could result in the grouted wasteform not meeting onsite disposal requirements. In these cases, Tc and/or Iodine removal as a pretreatment step would be considered as a risk mitigation. Additional LDR metal pretreatment is also considered as a potential mitigation process if the resulting wasteform fails the TCLP tests. The removal of Sr is considered a potential opportunity to change the waste classification of much of the resulting waste from Class B to Class A with a subsequent reduction in the disposal costs (CST ion-exchange may accomplish this as well). The conceptual flowsheets for pretreatment of Tc, I, LDR metal and Sr removal are implemented as either mitigation or as an opportunity to alter the waste classification. This flowsheet is discussed in detail in Appendix A.

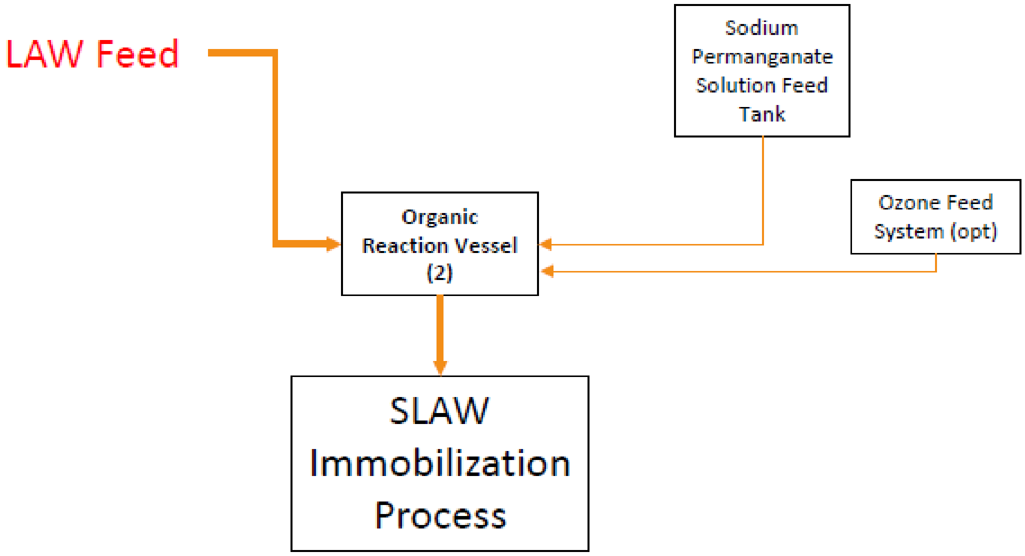

Figure 4 SLAW Pretreatment Concept with LDR organic treatment only

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Site Salt Waste Processing Facility, Technology Readiness Assessment Report," July 13, 2009, Prepared by the U.S. Department of Energy, Washington, D.C.

3.1.4 – Additional Areas for Evaluation

- Evaluate potential for exemptions from LDR requirements (e.g., no migration variance)
- Improve analytical methods to quantify levels of LRD organics in the feed vector.
- Demonstrate the oxidization of the full range of anticipated LDR organics either with permanganate alone or in combination with ozone.
    - Demonstrate a large-scale ozonation system.
    - Determine mixing parameters, residence time, oxidation rates, etc.
    - Determine whether the chemical oxidation results in the formation of other LDR organics.
    - Mature pretreatment technologies to TRL8.
- Evaluate feasibility of feed selection options (to redirect some high LDR organic SLAW to WTP) to minimize pretreatment scope for the grouting technology.
- Develop and demonstrate effective iodine removal from the caustic SLAW waste streams.
    - Develop an iodine wasteform compatible with the removal method.
- Confirm that grout formulations will pass TCLP.
- Confirm the extent of Sr removal using CST.

See full discussion of Pretreatment in Appendix A.

3.2 VITRIFICATION

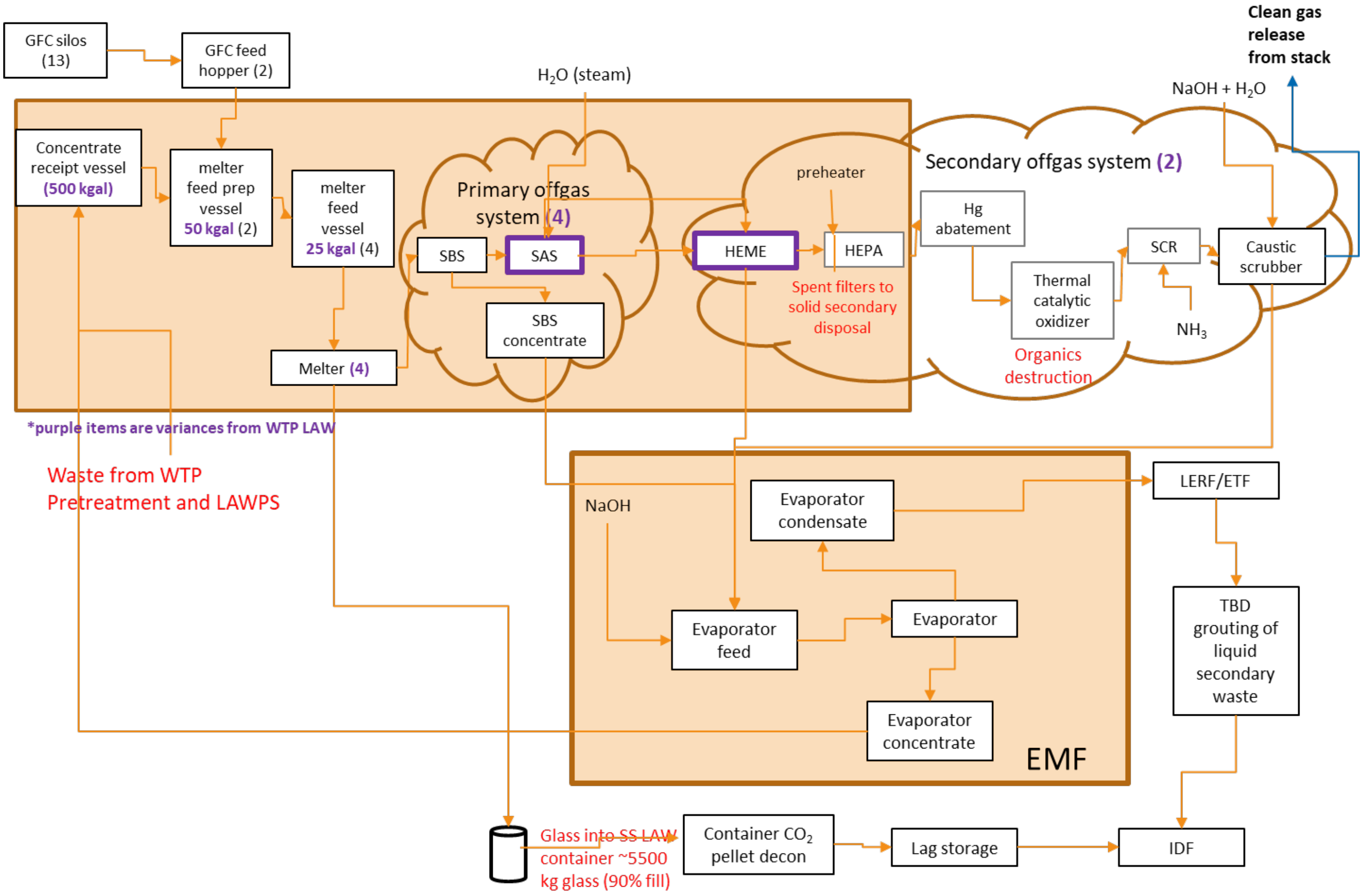
Vitrification blends radioactive liquid waste with glass-forming materials at high heat, forming a molten mixture that is poured into stainless steel canisters to cool and solidify into a glass wasteform that is highly stable in the expected conditions in a disposal facility. Vitrification technology has been used in the U.S. and other countries to treat high-level waste (HLW) for long-term, deep geologic disposal.

Vitrification for supplemental treatment of Hanford Low Activity Waste is summarized below and detailed in Appendix B.

3.2.1 Vitrification Technology

Waste vitrification technology consists of mixing a chemically characterized, aqueous waste stream with specific oxides and carbonates to produce a slurry that is fed to a melter in which the slurry is incorporated into the melt pool. The volatile components are driven into offgas by heat, generating a secondary liquid waste stream that also requires treatment. The molten glass is poured into a stainless steel container to cool. Vitrification unit operations are shown in Figure 5.

Figure 5 Vitrification unit operations



EMF	Effluent Management Facility
GFC	Glass forming chemical
HEME	High efficiency mist eliminator
IDF	Integrated Disposal Facility
LERF/ETF	Liquid Effluent Receipt Facility/Effluent Treatment Facility
SAS	Steam atomized scrubber
SBS	Submerged bed scrubber
SCR	Selective catalytic reduction
SS	Stainless steel

The waste components are chemically bonded as part of the glass wasteform, the interaction of the waste components with the glass-forming chemicals defines the amount of waste that can be immobilized in glass. The concentration and interaction among these components define the glass properties, such as durability. For LAW and Supplemental LAW, the Glass Shell v3.0 (a collection of property models) is used to constrain the composition and loading of LAW glasses to control the sulfur tolerance of the melter feed to durability response, viscosity, and refractory corrosion. The models also consider component concentration limits for chromium, halides, and phosphate. The models use the chemical composition (measured) of the waste to be vitrified. Preliminary calculations use the concentrations of sodium, potassium, and sulfur, to develop a target glass composition. Then, using the property models and the fourteen glass forming chemicals (GFCs) identified, the target glass composition is adjusted using the GFCs to maximize waste loading while meeting all the processing and performance constraints. The final properties and composition of the vitrified wasteform vary, but the models ensure that all the properties remain within acceptable processing and performance regions. The vitrified waste is poured using lifts into stainless steel containers. The canisters, filled to at least 90%, are cooled, sealed, and decontaminated, and are stored temporarily prior to IDF disposal.

The liquid secondary waste generated during vitrification is collected and processed through the Effluent Management Facility (EMF). Melter offgas condensate consists of components that are volatile and semi-volatile at melter temperatures. These species include Cl, F, I, Tc, Hg, As, S, and Se. As generated, the waste stream is near neutral in pH. For processing through EMF, the pH is raised to ~12. This causes the ammonium in the waste stream to partition to the overheads as ammonia. The EMF evaporator bottoms are recycled to the melter for retreatment.

The overheads are transferred to the Hanford Liquid Effluent Retention Facility/Effluent Treatment Facility (LERF/ETF) for collection and further treatment. The bottoms from ETF are primarily ammonium sulfate and the wasteform for the bottoms is currently under development. When treated, the wasteform will be disposed of in the IDF.

Solid secondary waste (HEPA filters, pumps, etc.) will be placed in a container, encapsulated in grout, and disposed of in the IDF.

Past assessments of ILAW performance have been based on the measured properties of a small number of glasses developed in the early stages of the program. The release of constituents of potential concern (COPCs) for these glasses has been used in all modeling efforts, including the EIS. As the focus on reduction of mission length via glass waste loading increased, glass property models were improved and higher waste loading regions of glasses were probed (Advanced Waste Glass). The release properties for these glasses are being generated; therefore, there has not been a Performance Assessment completed using these compositions. System Plan 8 uses an average sodium oxide loading of 22 wt% for the entire mission. Sodium oxide is one of the primary components that reduce the durability of the glass wasteform. For example, glass LAWABP1 used extensively for performance modeling contained 20 wt% sodium oxide. This glass also contained over 5 wt% zirconium oxide to inhibit glass dissolution (zirconium oxide concentrations in this range are not expected during LAW operation).

3.2.2 Vitrification Option for Hanford SLAW

This assessment considered three cases for SLAW vitrification. The base case used in System Plan 8 was used with modifications to vessel sizing and the offgas system to integrate with the primary LAW melters and the Balance of Facilities (BOF), and to increase the Total Operating Efficiency (TOE) to reach the 70% TOE required by System Plan 8. Some of the BOF constructed for HLW and the initial two ILAW melters are not sufficient to support SLAW. The silos for the fourteen GFCs do not have the capacity to feed the four SLAW melters. Additionally, the EMF being constructed to support offgas management for the initial two ILAW melters is not sized to support additional melters. These additional facilities will have to be constructed in addition to the four-melter glass plant. Additional facilities would be required to solidify the liquid secondary waste (there is an existing facility in operation that encapsulates solid secondary waste in grout, although new grout formulations are under development).

An alternative case would be to dispose of both the liquid and solid secondary wasteforms out of state. The current performance assessment identifies the secondary waste streams as the largest source terms for release of constituents of concern (CoC). By removing the contributions of the secondary wasteform from the IDF inventory, the higher waste loading advanced waste glass ILAW will not have to perform as well as previous waste glasses in the PA.

Another alternative evaluated is to use In-Container Vitrification™ (ICV). ICV performs the vitrification step in a carbon steel waste container lined with refractory material. The waste is blended with preblended GFCs, dried, and added to the waste container. The waste is vitrified and allowed to cool. The cooled container is disposed of in the IDF. The offgas is treated the same as the base case, transferred to the EMF, with bottoms returned to the melter feed and overheads transferred to the LERF/ETF for further treatment and grouting.

3.2.3 Vitrification Risks/Obstacles to Implementation

Selecting vitrification for Hanford SLAW carries both technical and programmatic risks/obstacles to implementations.

The vitrification option carries several technical risks primarily associated with project completion, but also with disposal of the wasteform:

- The vitrification process is inherently complex, primarily because of the extensive offgas treatment process required.
- Total Operational Efficiency (TOE) of 70% required to meet throughput requirements for System Plan 8 is not achieved.
  - If the TOE cannot be maintained at 70%, overall mission life will be extended, inflating operational expenses.
  - Variability in the feed rate will require frequent melter idling/restart in addition to idling incurred by preventative maintenance (e.g., bubbler replacement).
- Advanced glass compositions being developed to meet System Plan 8 throughput, do not meet Washington Ecology performance expectations/permitting requirements.
  - Until data is generated and input into a PA model for advanced glass compositions that were used to justify the throughput of ILAW and SLAW in System Plan 8, the program will have to rely on the waste glass compositions used in the prior PA and EIS.
- The single pass retention of technetium-99 and iodine-129 requires recycle of captured offgas components to the melter feed.
- Melter idling during operations of SLAW significantly decreases waste loading (S and halides) and increases liquid secondary waste volume and technetium-99 levels
  - Since melter idling is an operational necessity but was not considered in System Plan 8, the levels of semi-volatiles (such as technetium-99 and iodine-129) in the secondary waste streams are likely non-conservative in the recent PA that was based on the concentrations of these species from System Plan 8. The solid secondary waste streams are currently considered the greatest contributor to the release of CoC in the PA and the EIS; therefore, an evaluation is needed to ensure the assumptions in the PA remain valid during actual processing.
- Vitrification produces the secondary waste with the largest volume and highest curie content, which is evaluated as the dominant contributor to onsite disposal releases.

- Liquid secondary wasteform in early stages of development
  - The salt with the highest concentration in liquid secondary waste is ammonium sulfate. Since ammonium converts to ammonia in basic solutions, it is not routine to mix ammonium salts with cement-based components as the ammonia can be released. Research has been initiated to attempt to sequester the ammonium in a struvite mineral phase and encapsulate the mineral in a cement-based grouted wasteform.

Other risks associated with vitrification are primarily schedule and budget related:

- Applying Lessons Learned from WTP LAW may delay startup
  - System Plan 8 has Direct Feed LAW (DFLAW) startup in the latter part of 2023 and SLAW startup in the latter part of 2034. With a timeline of >10 years to build and bring a vitrification facility and associated support facilities online, construction will have to begin before DFLAW is operational. Lessons learned from the startup of DFLAW about design will have to be implemented immediately to meet the required facility startup.
- Funding for capital projects is insufficient to complete the facility and support facilities.
  - To meet the 2034 startup, the project will have to begin construction at the same time that HLW and pre-treatment are under construction. A significant increase in funding will be required to simultaneously support all of the capital projects at Hanford.

In this study, the mitigation of the TOE concern is 1) to increase the size of the vessels in the facility to provide lag storage to accommodate short, unplanned outages and 2) modify the offgas train to be modelled after the Defense Waste Processing Facility offgas train that has been in operation since 1996. To mitigate the issues associated with both the implementation of advanced glass compositions and melter idling increasing the liquid secondary waste, the option to dispose of the secondary waste streams at an offsite disposal facility was identified.

3.2.4 Vitrification Benefits

Benefits of vitrification as an option to address SLAW include:

- Design of facility can be leveraged from existing ILAW design (most technically mature technology)
- Wasteform has been studied extensively, so minimal further research is required
- High temperature destroys LDR organics and most nitrates
- Low primary waste volume.

3.2.5 Vitrification Costs

Based on the current LAW facility, vitrification has the highest estimated costs among the options evaluated, ranging from ~$20 to $36B, as shown in Table 4.

Table 4 Estimated costs ($M) for Vitrification

Vitrification	Low End	Analog Estimate	High End	Comments
Technology Development	340	-----------------------	760	Set at 5% of TPC
Pilot Operations	1080	1800	2520	See Note 2.
Total Project Cost (TPC)	6840	7600	15200	(-10% / +100%)
Operations (OPEX)	10080	12600	15120	(-20% / +20%)
Major Equipment	1400	-----------------------	2100	See Note 3.
Total Program Cost	19700		35700	

Vitrification costs note 1: Values are rounded.

Vitrification costs note 2: Pilot estimate driven by the integration of equipment, systems and type of testing. Pilot effort is assumed consistent for FBSR and Vitrification.
Vitrification costs note 3: Major equipment cost is driven by planned melter replacement and consumable melter bubblers. WTP-LAW melters have a nominal lifespan of 5 years. The 18 Inconel bubblers in each melter have a projected lifespan of 6 months. There will be nominally 24 melters required, each requiring 180 bubblers.

3.2.6 Vitrification Schedule

The estimated time to complete additional research & development, design, construction, and cold start (i.e., to hot startup) for the SLAW vitrification process is >10-15 years.

3.2.7 Vitrification Regulatory Compliance

Vitrified SLAW has been demonstrated for the PA and EIS to provide acceptable release of radionuclide and chemical species. Fifty containers of ICV SLAW have been permitted for disposal in the IDF as a demonstration.

Disposal of secondary waste at both IDF and WCS has been demonstrated to meet regulatory requirements, except that the levels of iodine-129 in the activated carbon require mitigation for IDF disposal. The disposal of secondary waste at the IDF is not included in the current permit. As noted above, Tc-99 and I-129 in secondary waste may be higher than assumed in the current IDF PA.

3.3 GROUTING

Grouting blends radioactive liquid waste with dry inorganic materials to produce a slurry that solidifies to encapsulate the constituents of concern in a moisture-resistant cement-like wasteform. Grouting has long been used to treat low level radioactive waste for near-surface disposal.

Grouting for supplemental treatment of Hanford Low Activity Waste is summarized below and detailed in Appendix C.

3.3.1 Grouting Technology

Grouting technology involves mixing an aqueous waste stream with various dry reagents to produce a mixture that is transferred into a waste container to solidify.

Grouting technology can be tailored for a range of waste chemistries, available cement ingredients, and process and final wasteform requirements. It can also be used to chemically retain certain radionuclides and hazardous contaminants by precipitation of low-solubility phases, by sorption on hydrated particle surfaces, by incorporation into layer structures of the hydrated phases, and/or by physically trapping dissolved constituents in the pore fluids within a low permeability solid matrix.

The final properties of a grouted monolith depend on a number of factors, including dry-mix components and proportions, the ratio of dry-mix to water, the composition of the liquid waste, curing conditions and times, etc. Thus not all grouts are the same. Cast Stone is one type of grout that has been developed for and tested specifically on a variety of Hanford Low Activity Waste streams. Cast Stone consists of a dry mix containing ordinary Portland cement (8 weight %), blast furnace slag (47 wt%), and class F fly ash (45 wt%), typically mixed in a water:dry-mix ratio of 0.4–0.6.

Cast Stone is similar to the grout formulation known as saltstone (with proportions 10:45:45), which was developed to solidify liquid wastes at the Savannah River Site (SRS). SRS has used saltstone since 1991, processing over 17 million gallons of liquid waste to date. The saltstone process involves pumping the grout slurry directly into large disposal vaults (termed “Saltstone Disposal Units” or SDUs), where it solidifies. In the primary grout processes considered in this analysis, the mixture is discharged into lined containers, where it is allowed to solidify before being transferred to the final disposal location. Large disposal units are addressed briefly as a potential alternative if grout disposal occurs at the IDF.

Curing of grout involves hydration reactions of the water in the waste feed with the dry-mix components to produce a cement-like monolith. Hydration of Cast Stone dry mix results in reaction products that include a range of phases. A suite of amorphous phases (including calcium silicate hydrate) dominate the reaction products, but ettringite and other crystalline alumino-ferrous sulfate phases have also been identified in hydration products from Cast Stone formulations.[29] The resulting solidified monolith consists of a porous solid (solid phases plus a pore space containing residual fluid); however, the small pore sizes and complex interconnected geometries serve to retain fluids through a variety of physical processes. This general characteristic of grout helps to retain many species within the solidified monolith, limiting release to the environment. Cast Stone creates a chemically reducing environment that stabilizes redox-sensitive contaminants such as pertechnetate and chromate, and it can be tailored (e.g., with getters) to enhance performance.

The materials used in the Cast Stone formulation are readily available at present, and the materials needs for a Cast Stone operation to handle projected volumes of SLAW is small compared with current domestic production.

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[29] e.g., Sundaram, et al., 2011; Um, et al., 2016

However, two of the reagents (blast furnace slag and fly ash) are associated with industrial processes that have experienced swings in domestic activity. In particular, the future availability of fly ash—which is produced during coal-based power production—was considered in the assessment, with the conclusion that the potential for alternative reagents (such as natural pozzolans) and/or stockpiling minimize any concerns over reagent availability being a limiting concern for Cast Stone.

Cast Stone is a grout formulation that has been tailored to the Low Activity Waste streams at Hanford. In laboratory studies, Cast Stone retains radionuclides of potential concern (technetium and iodine) better than assumed in previous assessments of grout performance; for example, the FFRDC team's preliminary assessment based on these more recent data suggest that Cast Stone may be able to retain Tc sufficiently well to meet performance goals. However, additional R&D would improve the understanding of these retention properties. Two grouting cases were assessed in detail: Grouting case I assumed IDF for final disposal, whereas grouting case II assumed the WCS facility (TX) for final disposal. Costs associated with constructing and operating a Cast Stone based grouting facility are estimated to be in the range of ~$2B to ~$8B, and the time to hot startup is estimated to be 8–13 years. Several potential risks were assessed, and mitigation options exist for each.

3.3.2 Grouting Options for Hanford SLAW

This assessment considered two general cases for a grouting process for SLAW: One case assumed disposal of the primary grouted wasteform at the IDF, and one case assumed disposal of the primary grouted wasteform at the WCS facility in Texas. A process flow diagram for the primary grout cases is shown in Figure 6. Detailed discussions of the cases (including process flow diagrams) are presented in Appendix C.

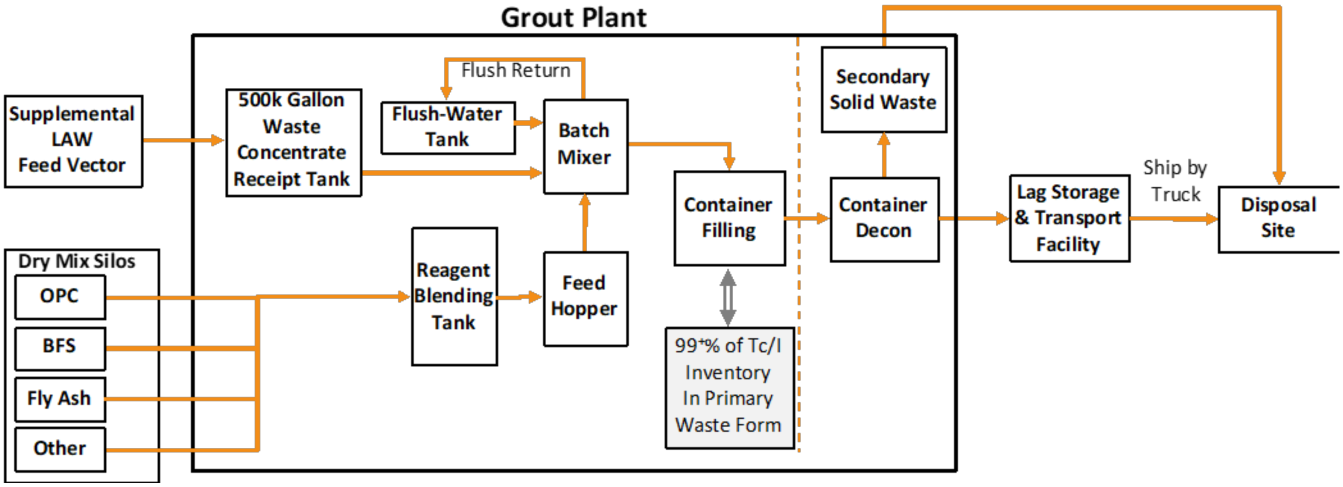

Figure 6 Process flow diagram for grouting

Both grouting cases were based on a Cast Stone formulation with a basic grout-plant process flow. A dry mix consisting of 8% ordinary Portland cement, 47% blast furnace slag, and 45% class F fly ash is blended and fed into a batch mixer where it is combined with the SLAW feed. The ratio of dry mix to liquid feed was assumed to be in the range 0.4–0.6. This slurry is then pumped into an 8.4 m^3 steel box lined with a polypropylene bag, where it is allowed to solidify prior to surface decontamination and shipping to the storage facility. The net result is an increase in the volume of the incoming liquid waste of ~1.8x. The secondary wastes generated in this process are minimal, due to the ambient temperature nature of the process (minimal offgas) and the incorporation of liquids into the primary wasteform (minimal-to-no liquid secondary waste stream). Hence, essentially all of the waste inventory resides in the primary wasteform.

Both grouting cases recognized the need to include a pretreatment step to address organic constituents associated with Land Disposal Restrictions (LDR) under the Resource Conservation and Recovery Act. As a low temperature process, grouting does not destroy organics present in the feed vector. The level of detail on organic constituents in tanks and, subsequently, in the anticipated feed vector is insufficient to analyze in detail pretreatment needs in the context of a Cast Stone process for SLAW; however, as described in Section 3.1.1.1, a screening analysis suggested that some LDR organics could be present in SLAW at levels requiring action; hence several possible pretreatment options were evaluated (see Appendix B). Pretreatment in the context of solidification of SLAW by a Cast Stone process represents an area for further analysis: specifically, additional work is needed to assess both the effectiveness of various pretreatment options and the ability to integrate a specific option with a Cast Stone process. Alternatively, organic-rich portions of the feed vector could be routed to the WTP LAW vitrification facility, sending only organic-poor liquids to a grouting facility. This approach could eliminate the need for pretreatment. Hence, the potential presence of LDR organics was recognized as an important consideration for both grouting cases. LDR metals—which also represent a consideration for both grouting cases—represent less of a factor, because grout has been shown to be an effective treatment. Several studies on Cast Stone have shown that LAW waste streams can pass TCLP (Westsik, et al, 2013a).

The primary assumptions in the analysis of both grouting cases included the following:

- The ranges and averages in feed vector composition are adequately captured by the System Plan 8. This assumption impacted several aspects of the analysis, including size of facility, disposal volumes, compatibility of grout with the feed vector, potential need for pretreatment, etc.
- LDR organics may be present in the SLAW feed. This assumption impacted the decision that pretreatment to destroy organics may be needed for any disposal site considered for grouted SLAW. An alternative strategy to address LDR organics could be to route any organics-rich LAW to the LAW vitrification facility, which could eliminate the need for an organics pretreatment step. The feasibility of this alternate strategy requires further analysis.
- Recent data showing lower values in release of Tc/I reflect more accurate measures of expected diffusion coefficients than values used in earlier assessments.

A primary focus for the assessment of grout-based systems in the context of storage at the IDF was whether the wasteform would be likely to retain Tc and I sufficiently well to meet performance criteria. (This factor is not relevant to disposal at WCS, which is already permitted to accept a grouted form of supplemental LAW because it complies with the waste acceptance criteria at WCS.) Anionic species of radionuclides (iodine and oxidized forms of technetium) were of particular interest, due to previous assessments of grouting that raised concerns about the long-term retention of these species. These earlier assessments were based on data for grout properties that pre-dated more recent testing on Cast Stone formulations. Hence, this assessment considered these more recent studies and explored the implications of these studies on the retention characteristics of Cast Stone with respect to supplemental LAW. The more recent studies generally measured retention using batch experiments, where the release data were interpreted in the context of effective diffusion coefficients, which were used to account for both chemical and physical retention in a diffusive-release scenario. However, the performance evaluation conducted as part of the FFRDC study considered release that accounted for both advection (transport by a moving fluid) and diffusion, so the effective diffusion coefficients reported in the recent experimental studies were re-cast as a diffusion coefficient coupled with a retardation factor. This re-casting is consistent with the methodology used in formal performance assessments (e.g., Reference the IDF PA). For details of the performance evaluation, see Appendix F. Nevertheless, the discussion that follows exploits effective diffusion coefficients in considering grout performance so that the dialog tracks with the experimental results reported in the literature.

Previous assessments—e.g., performance assessment, risk assessments, etc.—using diffusion coefficients based on early grout formulations showed a level of release of radionuclides that could endanger groundwater (e.g., Tc-99 release predicted by Mann, et al., 2003). However, recent studies have reported significantly lower effective diffusion coefficients for Cast Stone formulations, implying better retention characteristics than earlier formulations—particularly with respect to Tc retention (e.g., Westsik, et al., 2013a; Cantrell, et al., 2016; Serne, et al., 2016; Asmussen, et al., 2018). In contrast, the effective diffusion coefficients for iodine in a Cast Stone matrix appear to be comparable to those for nitrate, an aqueous species that is believed to be unaffected by chemical retardation effects in these systems (Westsik, et al., 2013a; Cantrell, et al., 2016; Serne, et al., 2016). Hence, the diffusion rate of iodine is determined by the physical properties of the monolith (e.g., porosity, tortuosity, fluid saturation). Some studies (Qafoku et al., 2014; Crawford et al., 2017; Asmussen, et al., 2018) have shown that chemical retardation of iodine can be enhanced by the use of specialized additives (termed iodine getters); the getters can be incorporated into the Cast Stone process, lowering the apparent diffusion coefficient for iodine.

The FFRDC team's performance evaluation considered retention characteristics using bounding values based on the recent experimental data, considering a both low performing and high performing retention characteristics. For Tc, low performing and high performing where based on the spread of value reported in Westsik et al. (2013a), whereas for I, low performing was based on values reported by Westsik et al. (2013a) but high performing was based on a consideration of retention exhibited in experiments with silver-based iodine getters (e.g., Crawford et al., 2017). The performance evaluation found that low performing cases would not retain Tc and I sufficiently well to meet groundwater requirements, but high performing cases would. It should be noted that the data on iodine getters are limited, but they serve as an example that development of an iodine-retention strategy for Cast Stone is feasible. Additional research will be needed to confirm and optimize of both Tc and I in Cast Stone. Details of the performance evaluation are in Appendix F.

3.3.3 Grouting Risks

The primary risk identified for selecting a Cast Stone process for SLAW is the potential presence of LDR organics. IDF and WCS must be RCRA compliant. As noted, there are several mitigation strategies for addressing this risk, including incorporation of a pretreatment step to remove organics or managing feed-vector flows such that only organic-poor liquids are sent to a Cast Stone process.

Another risk identified for selecting a Cast Stone process for SLAW is meeting the performance requirements for the IDF. Grouted wasteforms have not been permitted for disposal at the IDF. This risk could potentially be mitigated in several ways:

- Additional R&D that demonstrates grouted SLAW complies with long-term performance goals at IDF
- The removal (by pretreatment) of radionuclides of potential concern (Tc and I)
- The use of the WCS facility in Texas for the disposal of the grouted SLAW wasteform
    - Grouted SLAW meets the WCS radiological WAC.

The first of these mitigation options is based on recent studies on the retention properties of Cast Stone and on the use of getters, which suggest a significantly better performance for Cast Stone monoliths relative to previous assessment of grout performance.

Several other risks were considered in the analysis (Appendix C.4), including future availability of reagents. Each of the risks considered either has straightforward mitigation options and/or has a low likelihood.

3.3.4 Grouting Benefits

Benefits of grouting as an option to address SLAW include:

- Least-complex process of three options considered
- Ambient temperature process

    - Elimination of potential worker safety concerns associated with high temperature processes
- Minimal offgas, hence less solid secondary waste.
- Start/stop flexibility, which can accommodate variations in feed vector
- Lowest secondary waste volume due to minimal offgas treatment and no liquid secondary waste stream

3.3.5 Grouting Costs

Grouting has the lowest estimated costs among the options evaluated, ranging from ~$2B to ~$8B for Grouting Cases I (IDF) and II (WCS), as shown in Tables 5 and 6.

Table 5 Estimated costs ($M) for Grouting Case 1

Grouting Case 1	Low End	Analog Estimate*	High End	Comments
Technology Development	90	-----------------------	200	Set at 18% of TPC
Pilot Operations		-----------------------		See Note 2.
Total Project Cost (TPC)	500	560	1120	(-10% / +100%)
Operations (OPEX)	1120	1400	1680	(-20% / +20%)
Major Equipment	130	-----------------------	280	Set at 25% of TPC (Note 3)
Total Program Cost	1850		3280	

*The analog selected for grouting was SRS Saltstone. See Appendix H, “Cost Estimate Methodology and Results.”
Grouting costs note 1: Values are rounded.
Grouting costs note 2: Pilot is not recommended. No expected efficiency gain/impact to SLAW grout.
Grouting costs note 3: Based on SME input and Saltstone experience.

Table 6 Estimated costs ($M) for Grouting Case 2

Grouting Case 2	Low End	Analog Estimate*	High End	Notes
Technology Development	120	-----------------------	260	See Note 4.
Pilot Operations		-----------------------		
Total Project Cost (TPC)	650	720	1440	(-10% / +100%)
Operations (OPEX)	1120	1400	1680	(-20% / +20%)
Major Equipment	160	-----------------------	360	Set at 25% of TPC
Off-Site Trans/Disposal	2780	-----------------------	4163	SME Quote / 150% Quote
Total Program Cost	4820		7900	

*The analog selected for grouting was SRS Saltstone. See Appendix H, “Cost Estimate Methodology and Results.”
Grouting costs note 4: Technology development is provided as a function of TPC. The grout options considered have equivalent maturity. It is likely T&D will be equivalent and the differential value of estimated T&D costs is within total Program Cost uncertainty.

3.3.6 Grouting Schedules

For a grouting process, the estimated time to complete additional R&D, design, construction, and cold start (i.e., to hot startup) is 8–13 years.

3.3.7 Grouting Regulatory Compliance

Grouted SLAW is not currently permitted at IDF. However, there is a high likelihood of the primary wasteform meeting DOE performance criteria. There is a need for additional R&D to validate/demonstrate acceptable wasteform performance. Grouted SLAW would comply with the WCS facility WAC.

However, disposal at both IDF and WCS requires compliance with LDR under RCRA. Although grouting has the potential to address LDR metals (e.g., by demonstrating that wasteforms pass TCLP), organics are not inherently destroyed by the grouting process. Hence, some process considerations—e.g., pretreatment to destroy organics, or re-routing of organic-rich wastes to WTP LAW vitrification—may be needed. Several other exemptions or LDR compliance alternatives exist that may offer non-treatment compliance options for LDR organics.

Grouted SLAW would comply with Class C waste or less; in fact, it was estimated that only 33 months of the feed vector would result in a Class C waste designation, with the remaining 408 months being compliant with Class B.

Grouted SLAW would readily meet criteria needed to ship the waste as LSA-III.

3.3.8 Grouting Obstacles

Obstacles for grouting as an option to address SLAW include:

- Organics subject to LDR remain in grouted wasteform.
- Grout is not permitted at IDF. This obstacle applies only to disposal at IDF (Grouting Case I).
- Acceptable grout performance needs to be demonstrated. This obstacle also applies only to Grouting Case I (disposal at IDF). Demonstration of acceptable grout performance would require (i) conducting additional R&D to confirm Tc/I retention properties of new grout formulations, and (ii) conducting a formal performance assessment using updated retention characteristics applicable to new grout formulations.
- Highest volume primary waste.

3.4 STEAM REFORMING

Fluidized Bed Steam Reforming (FBSR) converts radioactive liquid waste to dry granular mineral particles with chemical structures that retain the radionuclides. FBSR has been researched, developed, and used commercially for over two decades for processing low level radioactive wastes.

FBSR for supplemental treatment of Hanford Low Activity Waste is summarized below and detailed in Appendix D.

3.4.1 Fluidized Bed Steam Reforming Technology

FBSR is a high temperature process that operates at temperatures up to 725-750°C to evaporate water in the waste, destroy organics, destroy nitrates, and convert the solid residue into a durable, leach-resistant wasteform. For treatment of Hanford SLAW, this process occurs in the Denitration and Mineralizing Reformer (DMR) vessel, which contains a bed of particles that are the right size and density to be continually fluidized by steam that flows up through the bed. The steam is superheated to nominally 500-600°C prior to entering the DMR. Coal and oxygen are fed into the DMR, where they react (also with steam) under stoichiometrically reducing (pyrolysis) conditions to heat the DMR to the target operating temperature and to produce hydrogen and other reduced gas species that react with the nitrates and nitrites in the waste feed, converting the nitrates and nitrites to nitrogen and water. Organics in the feed are efficiently pyrolyzed; nitrates in the feed are destroyed to below detectable levels in the mineralized wasteform; and about 95-99% of the nitrogen oxides (NO_x) are destroyed.

The remaining dissolved and undissolved components of the SLAW (such as sodium, aluminum, halogens, sulfur, hazardous metals, and radionuclides, if present) react with the clay that is premixed with the waste feed to form the desired mineralized wasteform. This product includes highly durable mineral structures of nepheline, carnegieite, sodalite, or nosean. These structures can incorporate the nonvolatile and semivolatile elements in the waste feed either into the nepheline or carnegieite mineral structures or inside sodalite or nosean "cages" of suitable sizes to contain halogens and radionuclides (Figure 7).[30]

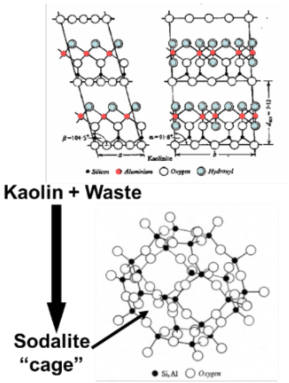

Figure 7 Sodalite "cage" contains halogens and radionuclides

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[30] Jantzen, C.M., E.M. Pierce, C.J. Bannochie, P.R. Burket, A.D. Cozzi, C.L. Crawford, W.E. Daniel, K.M. Fox, SRNL, C.C. Herman, D.H. Miller, D.M. Missimer, C.A. Nash, M.F. Williams, C.F. Brown, N. P. Qafoku, J.J. Neeway, M.M. Valenta, G.A. Gill, D.J. Swanberg, R.A. Robbins, L.E. Thompson, 2015, "Fluidized Bed Steam Reformed Mineral Wasteform Performance Testing to Support Hanford Supplemental Low Activity Waste Immobilization Technology Selection," SRNL-STI-2011-00387.

The relative proportions of these minerals in the wasteform depend largely on the amounts of halides, sulfur, and radionuclides relative to the amounts of total sodium and potassium in the SLAW. Modeling calculations for representative SLAW compositions indicate that the mineral product can nominally contain mostly (60-80 weight per cent) nepheline or carnegieite, 5-10 wt% sodalite, 6-12 wt% nosean, and 1-10 wt% silica (SiO_2) and alumina (Al_2O_3). The relatively small amounts of the sodalite and nosean minerals compared to the larger amounts of nepheline and carnegieite minerals in the model result from the relatively small amounts of anions and radionuclides (ranging from about 3-14 mole% of the sodium) and the sulfur (ranging from about 0.4-1 mole% of the sodium) in the SLAW feed vector.

3.4.2 FBSR Options for Treating Hanford SLAW

Two main FBSR cases were analyzed. Both produce a durable, mineralized primary wasteform for storage and permanent disposal. The differences between the two options are the disposal sites--Integrated Disposal Facility (IDF) on the Hanford site and Waste Control Specialists (WCS) site In Texas—as well as the FBSR processing steps needed to meet the requirements of those disposal facilities.

In both FBSR cases, two process systems in parallel receive waste from a single feed system to provide the throughput and ability to vary the throughput needed to maintain the SLAW feed vector.

Case 1 (Figure 8) produces a monolithic primary wasteform for storage and permanent disposal in the IDF on the Hanford site. Secondary wastes also are disposed of at IDF.

A geopolymer process downstream of the FBSR converts the granular FBSR product to a monolith, which is needed to meet the expected IDF 500 pound per-square-inch compressive strength limit.

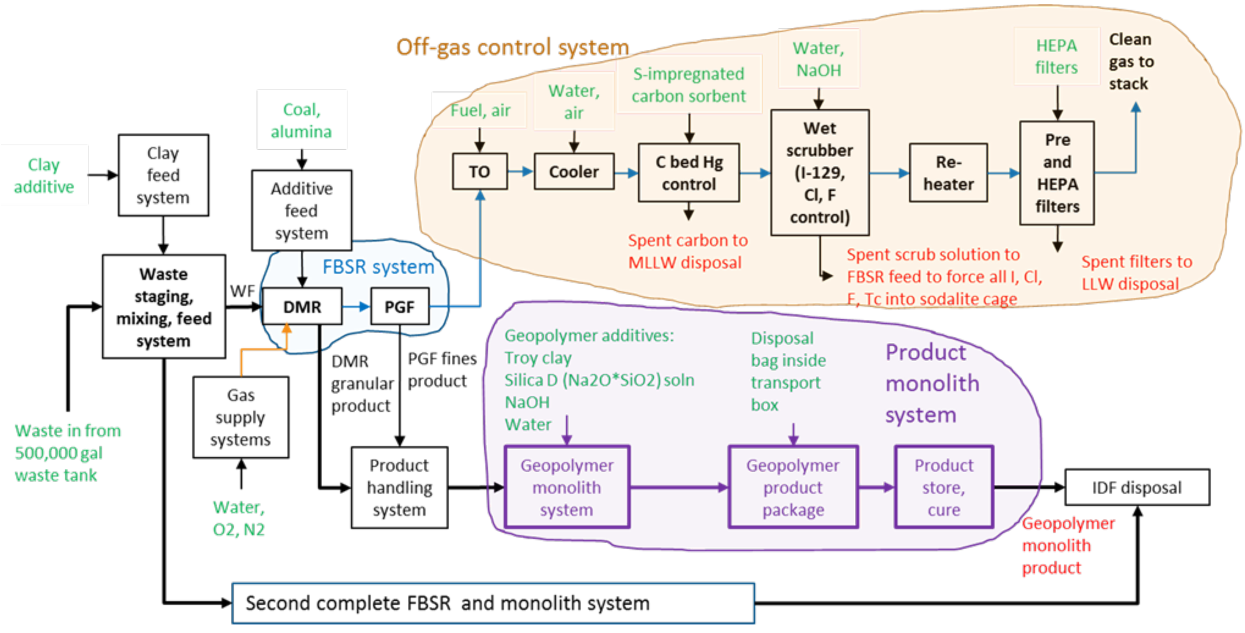

Figure 8 FBSR Case 1: Mineralized solid monolith product and secondary wastes disposed of at IDF

Case 2 (Figure 9) produces a solid granular primary wasteform for storage and permanent disposal at WCS. Secondary wastes also are disposed of at WCS in Texas.

WCS does not require a monolithic wasteform, so the geopolymer monolithing system is eliminated, making the Case 2 FBSR process simpler.

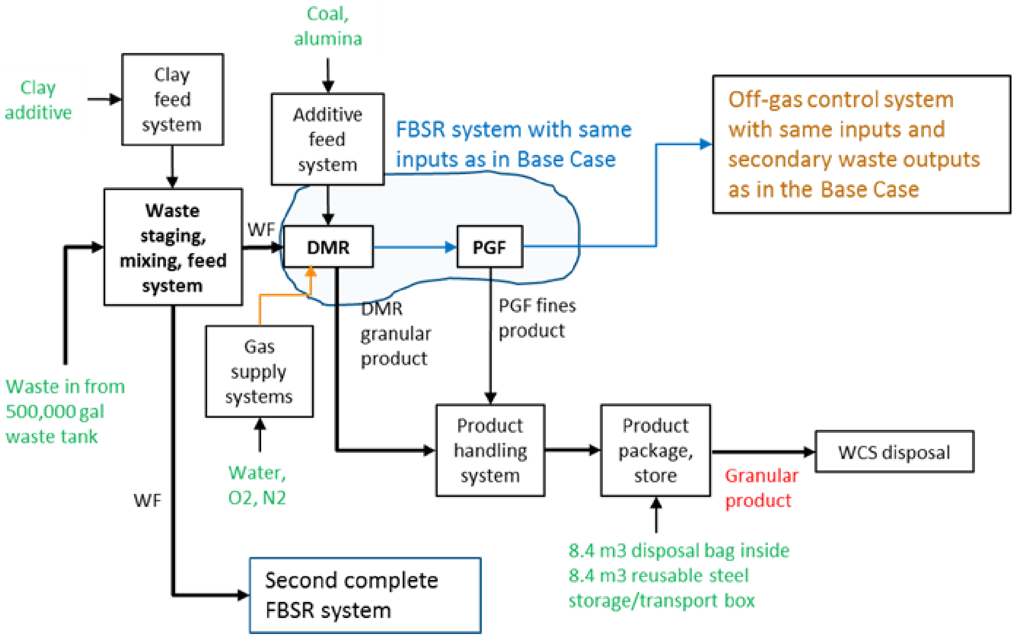

Figure 9 FBSR Case 2: Mineralized solid granular product and secondary wastes disposed of at WCS

These two cases bound the potential disposal options considered in this study. A variation on Case 1 is elimination of the monolithing system by the use of High Integrity Containers (HICs) that provide the IDF compressive strength limit. Other variations on Case 1 include shipping the secondary wastes to WCS instead of placing them in IDF. Variations on Case 2 could include disposal of some of either primary or secondary wastes in out-of-state low level waste (LLW) disposal sites other than WCS.

3.4.3 FBSR Risks and Obstacles

Major technical risks are

- FBSR has the lowest system, process, and equipment technical maturity for this application of treating the Hanford SLAW to produce a durable wasteform.
- The FBSR process is complex.
- Additional validation and demonstration of acceptable wasteform performance for Hanford onsite disposal are needed.
- Fluidized beds require rigorous process monitoring and control of waste feed injection, temperature, and fluidization to ensure stable operation.
- The granular solid mineralized product requires solids handling, filtration, and management.

A maturation plan including design, testing, and modeling is needed to address these technical risks. Other risks, and how the risks are mitigated, are described in Appendix D.

3.4.3.1 System, Process, and Equipment Technical Maturity

A plan to mature the FBSR process for Hanford SLAW treatment over several years is assumed to be needed to address the technical risks.

The commercial Erwin ResinSolutions Facility (formerly Studsvik Processing Facility) in Erwin, TN began operation in the late 1990s to treat radioactive wastes such as ion exchange resins with contact radiation levels of up to 100 R/hr. While the Erwin Resin*Solutions* Facility has operated at full scale for many years, the LLW it processes (primarily spent ion exchange resins from U.S. commercial nuclear power plants) is different from the Hanford SLAW. While its full scale operation uses equipment and subsystems that can translate to a Hanford SLAW treatment facility, some of these applications are indirect and in many cases not yet fully demonstrated for Hanford SLAW treatment at full scale. And while the Erwin Resin*Solutions* Facility also adds clay to produce a mineralized product, the significant difference in primary waste feeds makes the clay addition methodology different from the Hanford SLAW concept.[31]

Small-scale FBSR testing for treating liquid, highly acidic, radioactive sodium bearing waste (SBW) stored at the Idaho National Laboratory (INL) was initiated in 1999. Some of the design and operation of the Idaho Integrated Waste Treatment Unit (IWTU) is even more similar to a Hanford SLAW treatment process, but some subsystems have not yet been proven beyond pilot scale. The non-radioactive startup process for the IWTU, which started in 2012, has now gone several years beyond is initially planned duration and is not yet complete, mainly because equipment and subsystems that were proven in the full-scale Studsvik Processing Facility or in pilot-scale Engineering Scale Test Demonstration (ESTD) tests still have required demonstrations and modifications to make them function as needed at full scale in the IWTU.[32] (See Appendix D.)

The identification and resolution of IWTU challenges in areas such as process monitoring and control, process modeling, solids feeding, product solids handling, particle size control, and gas filtration have improved the technical maturity of steam reforming as applicable to a Hanford SLAW treatment process. Other IWTU startup challenges have been shown to be consequences of the design of the IWTU and the carbonate product chemistry. Incomplete gas fluidization and defluidization of bed particles were caused by the IWTU DMR design that injects feed from nozzles on only one side of the vessel, and bed particle stickiness (“sandcastling”) and wall-scale were caused by the carbonate product chemistry. The carbonate product chemistry is avoided when treating Hanford SLAW because of the goal to produce a mineralized product, which has been shown not to produce bed particle stickiness and wall scale. Full resolution of those challenges will increase the technical maturity of key FBSR components, and lessons learned from the IWTU can be incorporated into the design of a Hanford SLAW treatment process.

Some of the design and function of a Hanford SLAW FBSR treatment process would by necessity be different from those of the Erwin Resin*Solutions* Facility and the IWTU because the goal at Hanford is to produce a durable mineral wasteform versus a carbonate-based product. Pilot testing has shown, for example, that unlike a carbonate process, the mineralizing process does not produce particle stickiness and wall scale. However, unlike the IWTU DMR, the higher-temperature Hanford DMR may need to be refractory-lined. The higher operating temperatures may also cause changes to the PGF and other downstream subsystems.

Maturing some components to a high technical maturity will still require some technology maturation work. The estimated costs and schedule to mature all parts of a Hanford SLAW treatment process are included in the total FBSR costs and schedule for treating SLAW.

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[31] Mason, J. Bradley, Thomas W. Oliver, Marty P. Carson, and G. Mike Hill. 1999. “Studsvik Processing Facility Pyrolysis/Steam Reforming Technology for Volume and Weight Reduction and Stabilization of LLRW and Mixed Wastes,” WM’99, February 28-March 4, 1999.

[32] Giebel, Joseph E., James P. Law, Craig L. Porter, H. Bradley Eldredge, and J. Brad Mason. “Steam Reforming Process for Treating Radioactive Waste,” WM’18, March 18-22, 2018.

3.4.3.2 Wasteform Performance

The 2012 Hanford Tank Closure and Waste Management Environmental Impact Statement (EIS) concludes, among other things, that "…The steam reformed wasteform would not be equal to that of the WTP glass…"[33] Other documents contemporaneous to the 2012 EIS drew different conclusions. The National Research Council "Wasteforms Technology and Performance, Final Report," (NRC 2011) concludes "…crystalline ceramic wasteforms produced by FBSR have good radionuclide retention properties and waste loadings comparable to, or greater than, borosilicate glass. This wasteform material is also potentially useful for immobilizing LAW."[34]

Since both the 2011 National Research Council report (NRC 2011) and the 2012 TC and WM EIS, the mineral wasteform produced from the mineralizing FBSR process was studied more extensively between 2012-2015 (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015]). Based on results of these studies, it seems that some conclusions of the 2012 TC and WM EIS might need to be re-evaluated. These most recent results indicate that the FBSR process has a high likelihood to meet DOE technical performance criteria for onsite disposal (IDF) (e.g., DOE Order 435.1) and for offsite transport and disposal at WCS (TX). More detail on the results of the 2012-2015 studies is provided in Appendix D.

Other risks and possible mitigations are summarized in Appendix D. One of these risks is that that the process cannot operate with at least 70% total operating efficiency (TOE), as assumed. Two options could mitigate this risk. The first is to take up to a one-year delay in startup in order to design, demonstrate, and optimize the process to reach 70% TOE. A second option is to add up to one million gallons of lag storage if the TOE is only 50%. If both options fail or are not opted for, and if a 50% TOE is achieved, then this could cause a one-year delay in the first three years of the feed vector. After the first three years, a TOE of 50% or less is sufficient to maintain the feed vector schedule.

FBSR can be expected to carry other risks normally associated with high temperature processes, which are mitigated by methods established and proven in nuclear and other industries.

3.4.4 FBSR Benefits

Benefits that FBSR can provide for treating the Hanford SLAW include:

- Tolerance of feed vector variations and integrated system process upsets that change the feed vector flowrate or compositions: If integrated system upsets that cause unplanned feed vector changes occur, FBSR may have the flexibility to shut down temporarily or be operated with reduced feedrate.
- Efficient destruction of hazardous organics, nitrates and NOx, and ammonium compounds.
- According to recent wasteform durability tests [SRNL-ORNL-PNNL-WRPS downselect (Jantzen 2015)], the production of a durable wasteform without increasing waste volume during treatment and without liquid secondary wastes.
- The lower temperature of the process versus vitrification reduces the amount of semivolatiles that partition to the offgas, minimizing the "flywheel" concentrations of volatile and semivolatile elements.

3.4.5 FBSR Costs

The costs for the Hanford SLAW FBSR concept range from ~$7B to ~$16B, as shown in Tables 7 and 8. The detail of these costs are provided in the cost estimating sections of this report and Appendix D.

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[33] DOE 2012, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington, (TC & WM EIS)," DOE/EIS-0391, November.

[34] NRC 2011, "Wasteforms Technology and Performance, Final Report," National Research Council of the National Academies, Committee on Wasteforms Technology and Performance, National Academies Press, Washington, DC.

Table 7 Estimated costs ($M) for FBSR Case 1

FBSR Case 1	Low End	Analog Estimate*	High End	Comments
Technology Development	480	------------------------	1080	Set at 25% of TPC
Pilot Operations	1080	1800	2500	See Note 2.
Total Project Cost (TPC)	1930	2150	4300	(-10% / +100%)
Operations (OPEX)	2520	3150	3780	(-20% / +20%)
Major Equipment	290	-----------------------	650	Set at 15% of TPC (Note 3)
Total Program Cost	6300		12330	

*The analog selected for steam reforming was INL Integrated Waste Treatment Unit. See Appendix H, "Cost Estimate Methodology and Results."
FBSR costs note 1: Values are rounded.
FBSR costs note 2: Cost is estimated for integrated WTP (with SLAW) pilot to optimize operations with process rates and system outage/downtime.
FBRS costs note 3: Based on SME input and IWTU development / startup.

Table 8 Estimated costs ($M) for FBSR Case 2

FBSR Case 2	Low End	Analog Estimate	High End	Notes
Technology Development	480	---------------------	1080	Held Constant w/ FBSR Case 1
Pilot Operations	1000	1800	2600	
Total Project Cost (TPC)	2310	2570	5140	(-10% / +100%)
Operations (OPEX)	3270	3920	4900	(-20% / +20%)
Major Equipment	330	-----------------------	740	Set at 15% of TPC
Off-Site Trans/Disposal	1850	-----------------------	2780	SME Quote / 150% Quote
Total Program Cost	9240		17,240	

*The analog selected for steam reforming was INL Integrated Waste Treatment Unit. See Appendix H, "Cost Estimate Methodology and Results."

3.4.6 FBSR Schedule

A range of 10-15 years is estimated for the time needed to progress through technology development, pilot plant testing, plant design, construction, startup, and readiness for hot startup. The time duration for the IWTU from pilot-scale testing at Hazen (2005) to now (2019) is 14 years, although 7 of those years occurred after the IWTU was constructed and started up. The technology maturation plan assumed in this study provides more time and funding for technology development and pilot plant operations to enable less time and cost for testing and modifications after plant construction. The technology maturation plan and full-scale design is expected to benefit greatly from the IWTU experience, though that potential benefit is not assumed in the current cost and schedule estimates.

3.4.7 FBSR Regulatory Compliance

Steam-reformed SLAW is not currently permitted at the IDF facility. However, there is a high likelihood of the primary wasteform to meet DOE performance criteria. There is a need for additional R&D to validate/ demonstrate acceptable wasteform performance.

The steam reformed wasteform meets the WAC for disposal at WCS.

The FBSR process can be operated in full compliance with applicable regulations, as demonstrated in general with the Erwin ResinSolutions facility and the IWTU.

FBSR is expected to meet emission requirements similar to WTP LAW vitrification. FBSR air emission compliance has been demonstrated in multiple pilot-scale tests, and is planned for demonstration in the IWTU prior to, and at the beginning of, radioactive operations. Testing has demonstrated compliance to the stringent Hazardous Waste Combustor (HWC) Maximum Achievable Control Technology (MACT) standards. This pyrolysis/oxidation combination can also destroy ammonia compounds that could be in liquid secondary wastes from WTP vitrification and in the SLAW feed vector. Since the FBSR process does not require NO_x selective catalytic reduction (SCR), no ammonia is fed into the offgas system, and no “ammonia slip” occurs that can be problematic if the SCR operation becomes less controlled or is subject to variations in the incoming NO_x concentrations.

3.5 OTHER APPROACHES

The scope of this study is explicitly prescribed in NDAA17 Section 3134:

> ***"… An analysis of <u>at a minimum</u>, the following approaches for treating the Low Activity Waste …:***
>
> *(A) <u>Further processing</u> of the Low Activity Waste to remove long-lived radioactive constituents, particularly <u>technetium-99 and iodine-129</u>, for immobilization with high-level waste.*
>
> *(B) Vitrification, grouting, and steam reforming, <u>and other alternative approaches identified</u> by the Department of Energy for immobilizing the Low Activity Waste."*

Further processing (i.e., pretreatment) options and the three specified immobilization options – vitrification, grouting, and steam reforming--are summarized in, respectively, sections 3.1, 3.2, 3.3, and 3.4 of this chapter. This section focuses on the identification, evaluation, and screening of other alternative approaches, including approaches for further processing and immobilizing Hanford LAW.

It is noted that commercial facilities that currently perform treatment of radioactive wastes may be suitable for treatment of the SLAW. It is expected that these facilities would ultimately generate a grouted or steam reformed wasteform for disposal at an out-of-state disposal site. These treatment facilities were not evaluated during this study.

A wide range of LAW processing options has previously been identified and considered,[35,36,37] including supplemental treatment options that identified the three immobilization approaches specified in NDAA17. Given the extent of previous options analyses, the FFRDC team's approach to assessing other options comprised:

- Identification of options considered in earlier supplemental treatment selection studies
- Review of the rationale for each option's earlier disposition (e.g., screened out, recommended for further consideration)
- Assessment of any subsequent development or evaluation of each technology option to assess whether the status is still appropriate given potential new information and data
- Evaluation of the relevance of the option to the scope of the NDAA17 study, potential benefits to the supplemental treatment mission, and likelihood that those benefits could be realized if pursued.

Nine alternative approaches were identified from a review of prior tank waste processing and supplemental LAW treatment alternatives evaluations. Three alternative approaches represented immobilization options, while the other six represented further processing options. The team identified four additional alternatives based on its identification of potential gaps or opportunities within the three primary immobilization alternatives specified. Of the total of thirteen approaches, four pretreatment alternatives—technetium removal, iodine removal, strontium removal, and treatment of RCRA LDR constituents—were considered either key to NDAA assessment scope for the grouting immobilization option or potential opportunities warranting further evaluation. These alternatives are described and evaluated in Section 3.3.

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[35] Choho and Gasper. "Evaluation of Low-Activity Waste Feed Supplemental Treatment Options for the C3T Mission Acceleration Initiative Team for the Office or River Protection." RPP-11306, Revision 0. 2002. CH2M HILL Hanford Group, Inc. Richland, Washington

[36] DOE. "Tank Closure and Waste Management Environmental Impact Statement." DOE/EIS-0391 FINAL. November 2012. U.S. Department of Energy.

[37] R.E. Raymond, R.W. Powell, D.W. Hamilton, W.A. Kitchen, B.M. Mauss, and T.M. Brouns. "Initial Selection of Supplemental Treatment Technologies for Hanford's Low-Activity Tank Waste." RPP-19763-FP, Revision 0. February 2004. Presented at Waste Management 2004 Symposium, Tucson, AZ. CH2MHill Hanford Group, Inc., Richland Washington.

The remaining nine alternatives were assessed and determined to be outside the scope of the NDAA17 study, not to have significant benefit to the tank waste mission or study scope, or to represent a variant of another primary processing alternative being evaluated. Therefore, these alternatives did not warrant further evaluation within the study scope. Table 11 provides a summary of these other alternatives considered.

Table 9 Other Alternatives Identified For Study Consideration

TECHNOLOGY OPTION	KEY ATTRIBUTES	SOURCE	MAJOR ALT., VARIATION, OR SUPPLEMENTAL TO PRIMARY OPTIONS	NDAA17 STUDY ASSESSMENT AND DISPOSITION
Immobilization Alternatives				
Vitrification with Phosphate Glass	Increased sulfate and chromium loading in glass, increased vitrification throughput	DOE, 2014[36]	Variation of vitrification base case	Iron phosphate glasses offer potential benefits over borosilicate glasses such as sulfate tolerance, but with tradeoffs including lower technical maturity (e.g., need for testing at scale and melter corrosion performance) than the vitrification base case. The base case borosilicate glasses and advanced LAW glasses being studied represent a more mature and lower technical risk case for this study. Phosphate glasses do represent a potential opportunity; however, the benefits are expected to be incremental to those of advanced LAW borosilicate glasses. *No further evaluation pursued.*
Active-metal reduction	Nitrites and nitrates are destroyed in reactions with aluminum metal. A phosphate-based ceramic wasteform is produced.	Choho and Gasper, 2002[35] Gasper et al., 2002[38] DOE, 2014[36]	Major alternative	Low technical maturity with higher technical and safety risk than current approaches. No evidence of development or maturation since original 2002 assessment. *No further evaluation pursued.*
Alternative low-temperature wasteforms such as phosphate-bonded ceramics and alkali-aluminosilicate geopolymers	Potential increased durability over cement-based wasteforms at low temperature processing	Cantrell and Westsik, 2011 Gong et al., 2011[39] Josephson et al., 2011[40]	Variation of low-temperature grouting base case	These wasteforms were tested and evaluated alongside cementitious wasteforms as a low-temperature alternatives for secondary waste stream treatment from Hanford tank waste processing. Benefits associated with these wasteforms were not deemed significant relative to the grouting base case, based on the results of secondary waste treatment testing and evaluation. In addition, these wasteforms are at a lower technical maturity than the grouting base case for LAW treatment. *No further evaluation pursued*.
Pretreatment Alternatives				
Fractional crystallization	Separate Cs, Tc, I from a high sodium fraction of the LAW	DOE, 2014[36] Herting, 2007[41]	Supplemental to base cases and variants	Primary benefit is to provide for decontamination of Cs-137, and potentially Tc-99 for low- to medium-curie tank wastes in lieu of the baseline Cs pretreatment which includes Tank Side Cesium Removal (TSCR), LAWPS, and the WTP Pretreatment facility. Alternative Cs removal is considered outside NDAA scope. Tc removal via fractional crystallization is at low technical maturity, and the process would only address a fraction of the SLAW feed vector. The process may have applicability within hybrid options that involve tank- or farm-specific treatment of 23SLAW. However, these options were not within the primary scope of the NDAA17 study. *No further evaluation pursued*.
Clean salt (with or without sulfate removal)	Separate a "clean" sodium nitrate (and optional sulfate) fraction for immobilization in ceramic, grout, or polymer.	Choho and Gasper, 2002[35] Gasper et al., 2002[38] DOE, 2014[36]	Supplemental to base cases and variants	Technology provides an alternative to baseline Cs pretreatment, with potential added benefit of Tc removal. Radionuclides are washed out of crystallized sodium nitrate salts. The relatively clean salts would still be managed as MLLW and require stabilization in a low-temperature wasteform. Alternative Cs removal considered outside NDAA scope. Benefits of grouting clean salt verses grouting LAW stream directly not considered significant. Process will slightly increase total waste requiring stabilization. *No further evaluation pursued*.
Plasma mass separator	Physical separation of elements by atomic mass to produce heavy and light fractions for treatment	DOE, 2014[36]	Major alternative for improved separations prior to immobilization	The plasma processing technology has low technical maturity and high technical risk based on earlier development efforts. Commercial development ceased in 2006. This process is principally focused on reducing HLW volume, with only modest reduction in LAW volume; therefore, it is not core to the NDAA17 study scope. *No further evaluation pursued*.

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[38] Gasper, KA, KD Boomer, ME Johnson, GW Reddick, Jr, AF Choho, JS Garfield. "Recommendation for Supplemental Technologies for Potential Mission Acceleration." RPP-11261, Revision 0. 2002. CH2M HILL Hanford Group, Inc. Richland, Washington

[39] Gong W, W Lutze, and IL Pegg. "DuraLith Alkali-Aluminosilicate Geopolymer Wasteform Testing for Hanford Secondary Waste." VSL-10R2140-1. 2011. Vitreous State Laboratory, The Catholic University of America, Washington, D.C.

[40] Josephson, GB, JH Westsik, Jr., RP Pires, JL Bickford, MW Foote. "Engineering-Scale Demonstration of DuraLith and Ceramicrete Wasteforms." PNNL-20751. 2011. Pacific Northwest National Laboratory, Richland, Washington.

[41] Herting, DL. "Fractional Crystallization Flowsheet Tests with Actual Tank Waste." RPP-RPT-31352, Revision 1. 2007. CH2M HILL Hanford Group, Inc. Richland, Washington

TECHNOLOGY OPTION	KEY ATTRIBUTES	SOURCE	MAJOR ALT., VARIATION, OR SUPPLEMENTAL TO PRIMARY OPTIONS	NDAA17 STUDY ASSESSMENT AND DISPOSITION
Caustic recycle	Electrochemical separation of sodium hydroxide for recycle, reducing LAW volume	DOE, 1999[42] Poloski et al. 2009[43] Wilmarth et al. 2007[44]	Supplemental to base cases and variants	Primary benefit is the reduction in need for additional sodium hydroxide to support HLW sludge processing, thereby reducing the total mass and volume of the SLAW feed vector, but not eliminating the need for SLAW treatment. Technical and economic assessments conducted in 2007-2009 were favorable. Pretreatment for sodium reduction is not core to the NDAA17 study scope. The process may warrant further consideration as part of the overall HLW sludge pretreatment program. *No further evaluation pursued.*
Technetium removal	Reduce Tc-99 in LAW fraction or secondary waste	DOE, 2014[36]	These four pretreatment alternatives—technetium removal, iodine removal, strontium removal, and treatment of RCRA LDR constituents—were considered either key to NDAA assessment scope for the grouting immobilization option or potential opportunities warranting further evaluation. These alternatives are described and evaluated in Section 3.1.	
Iodine removal	Reduce I-129 in LAW fraction or secondary waste	DOE, 2014[36]		
Strontium removal	Reduce soluble Sr-90 in specific LAW feeds	NDAA17 FFRDC Study Team Assessment and Identification		
Treatment of RCRA LDR Constituents	Oxidation or reduction to destroy organics or reduce metal mobility in LAW wasteform (e.g., grout)	NDAA17 FFRDC Study Team Assessment and Identification		
Ammonia removal	Reduce emissions and safety concerns during waste processing	NDAA17 FFRDC Study Team Assessment and Identification	Supplemental to grouting base cases and variants	The need for ammonia treatment within the low temperature grouting base case and variants has not been confirmed at this stage of pre-conceptual design and assessment. If needed, it is expected that ammonia abatement would be integrated into a grouting facility offgas treatment system and would be specified during detailed project definition. *No further evaluation pursued.*
Hybrid Alternatives				
Modular Processing of Tank Waste – tailored to specific tanks, farms, or processing areas.	Tank side, or local processing capability tailored to pretreat and/or immobilize specific wastes. Reduce need for a single robust facility to treat wide range of wastes to be encountered.	NDAA17 FFRDC Study Team Assessment and Identification	Supplemental to SLAW treatment options	The primary benefit of modular processing is the potential to treat specific tank wastes earlier, with lower capital expenditures for limited throughput processing. This hybrid option may also enable processing of problematic wastes with tailored processes, avoiding the need to build more capacity and capability into the larger primary process facilities. Hybrid options involving modular processing were not considered within the core NDAA17 study scope, as they are not addressing the full SLAW feed vector. However, there is the potential opportunity to mature processing technology and/or achieve earlier SLAW processing via smaller-scale modular processing, as is being pursued by DOE with the RSCR pretreatment project and the Test Bed Initiative.

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[42] DOE. “Innovative Technology Summary Report: Caustic Recycle.” DOE/EM-0494. 1999. US Department of Energy, Washington DC.

[43] Poloski, AP, DE Kurath, LK Holton, GJ Sevigny, MS Fountain. “Economic Feasibility of Electrochemical Caustic Recycling.” PNNL-18265. 2009. Pacific Northwest National Laboratory, Richland, Washington.
at the Hanford Site

[44] Wilmarth, WR, DT Hobbs, WA Averill, EB Fox, RA Peterson. “Review of Ceramatec’s Caustic Recovery Technology.” WSRC-STI-2007-00366, REVISON 0. 2007. Washington Savannah River Company, Aiken, South Carolina.

4.0 HIGH-LEVEL COMPARISON OF THE FIVE CASES FOR HANFORD SLAW IMMOBILIZATION

The team evaluated each of the three immobilization technologies specified in NDAA17, eventually selecting five representative cases, specifically one for vitrification and two each for grouting and steam reforming to accommodate both onsite and off-site disposal options.

The summaries and table in the two sections below present high-level comparisons of the five cases of the three immobilization technologies specified in the NDAA17 in regard to the criteria specified in the NDAA17 as well as evaluation and selection challenges identified by the team.

4.1 COMPARISON PER ANALYSIS CRITERIA SPECIFIED IN NDAA17

The following summaries and table present a high-level comparison of the five cases in regard to the criteria specified in the NDAA17.

4.1.1 Risks/Obstacles To Implementation

All three immobilization technologies carry some technical performance risks. Vitrification is a mature technology but is the most complex so has the highest risk of not meeting throughput targets. Grouting may require development of a pretreatment process to remove organics subject to Land Disposal Restrictions (LDRs). Steam reforming is the least mature technology requiring the most technology development, with the attendant risks of uncertain outcomes.

Total funding needed for total tank waste disposition represents a programmatic risk common to all technologies considered for SLAW. The high capital cost of vitrification also represents a high programmatic risk.

Transportation

The FFRDC analysis concluded that the primary and secondary wasteforms can be safely transported from Hanford to the WCS disposal facility in Texas. The primary wasteforms from both grouting and steam reforming meet the NRC criteria to be shipped as low specific activity material, the NRC’s least hazardous category of material for shipping. The secondary wasteforms will need to be shipped in Type A boxes, but no wasteform will require the Type B shipping cask.

Transportation for Grouting Case II WF, on average, will require a single train with 26 gondola railcars per month for the 28-year immobilization and disposal effort. Transportation of the Steam Reformed Case II WF, on average, will require a single train with 8 gondola railcars per month. A train every 3 months with 78 gondola rail cars (Grout) or 24 gondola railcars (Steam Reformed) could reduce the impacts of the shipping program. The technology readiness level is very high, as the DOE currently ships similar wastes for off-site disposal by rail.

Actuarial risk was analyzed for both out-of-state disposal cases. Statistically, the 28-year program would increase national rail fatalities on the order of o.oo7 perfect. This risk in not included in Table 10.

See full discussion of Transportation in Appendix G.

4.1.2 Benefits

Vitrification results in the lowest primary waste volume and would be able to utilize experience from WTP LAW facility startup and operations. The high temperature of the vitrification process would be expected to destroy any organics and most nitrate in the feed. A grouting process would require the organic constituents to be addressed by pretreatment or by altering the feed selection to the process.

Grouting was deemed the most compatible with a highly variable feed volume due to the ability to start and stop the process much more easily than vitrification or steam reforming. Grouting was determined to be the least complex technology, operating at ambient temperature, and requiring the fewest controls of the three technologies. Grouting does not result in a significant secondary waste stream since the low-temperature process does not lead to volatilization of feed components and the water in the waste stream is incorporated into the final wasteform. The secondary waste streams (solid and liquid) from vitrification are planned to be disposed of in a grouted wasteform.

Steam reforming has the benefit of being the lowest-cost process that can produce a durable wasteform, avoid increasing the waste volume, provide high temperature LDR organics destruction, and destroy nitrates without pretreatment or feed alteration. Steam reforming is expected to have better retention of technecium-99 and iodine-129 than vitrification, which will result in lower losses of these species to secondary waste.

4.1.3 Costs

The Total Program Cost (TPC) estimates for the three technologies show considerable variation. Vitrification has the highest projected cost range, FBSR is second, with grouting calculated to be the lowest cost option. There are 4 main portions of the individual cost estimates that determine the final TPC rankings.

1. Technology Development and Pilot Operations
2. Total Project Cost (effectively the capital project for SLAW)
3. OPEX/Life Cycle Cost
4. Shipment to / Disposal at WCS

Technology Development and Pilot Operations are significantly higher for vitrification and FBSR due to the nature of the testing (vitrification) and degree of maturity relative to the waste stream and application (FBSR). Technology development and testing for vitrification will be predominately focused on product rate and integrated operations. All primary HLW and LAW treatment will be vitrification based, resulting in the largest total volume of primary plus secondary liquid waste to be processed through WTP-PT. Integrated testing to verify rate attainment and system interfaces between facilities will require significant system capability so as to provide necessary operational data, including extended duration testing for total system reliability. SLAW is reliant on WTP-PT and WTP-HLW, ergo integrated testing will be a significant investment.

FBSR is the least mature of the technologies for caustic liquid feed processing. The closest operational analog (IWTU) is designed to produce a carbonate product from acidic feed at INL. That the wasteform and the process design, process equipment, and integrated system meet SLAW treatment requirements needs to be demonstrated in pilot and full-scale operation.

Grouting has been demonstrated at scale for inherently similar caustic waste. However, the operational requirement to meet LDR must be developed and the associated unit operation(s) demonstrated. This effort will be the major facet of the T&D necessary to fully evolve grout for SLAW through to the capital project.

Total Project Cost estimates reflect current WTP costs captured (WTP-LAW, Balance of Facility, and DFLAW) as per SLAW vitrification. It is recognized that these costs appear significantly greater than projected in the EIS; they are more in line with the recent GAO reporting and current ORP System Planning values, which rely on updated WTP project costs. The project cost for the SLAW vitrification complex is considerable. Project completion of the SLAW complex by 2034 will mandate no fewer than 6 years wherein SLAW and WTP-PT plus WTP-HLW each require the current WTP line item (assumed here at $750M per year) for completion. To complete these facilities will require 2X for these years. This funding scenario is not consistent with the demonstrated path for the current WTP complex.

Project costs for the FBSR or grout facility are derived from the closest analogs and scaled (FBSR) to match capacity or cost escalated (due to the age of SRS Saltstone) to 2018. Grout is also amended to provide for significantly enhanced handling and logistics to include the LDR treatment – aspects not incorporated at Saltstone. Upgrades for pre-treatment and logistics/handling significantly increase the TPC for grout versus simply escalating Saltstone costs. At the same time, the projected costs are nominally consistent with other recent estimates and do not mandate doubling (as per vitrification) of capital outlay in conjunction with WTP-PT and WTP-HLW completion.

<u>OPEX/Life-Cycle</u> cost estimating is based on the current project estimate for DFLAW (vitrification), IWTU start-up operational costs (FBSR), and Saltstone (grout). Grout OPEX costs are significantly increased to provide for the LDR treatment unit operation(s) and handling/logistics issues. These OPEX costs are projected significantly lower than FBSR, which is in turn less than DFLAW operation estimates (even accounting for removal of LAWPS, etc.). It is noted this the largest gap between technologies and no overlap exists between associated cost ranges. high temperature processing is consistently shown to be higher in operating costs in the DOE complex and for international operations.

<u>Shipment to / Disposal at WCS</u> is a significant estimated cost for FBSR and the single highest cost source identified for grout (up to 50+% of TPC). This cost is inherent to off-site disposition and so is not appropriate for vitrification – at least regarding primary wasteform disposition. Off-site disposition for grout equates to the range of 30-60 percent of the vitrification capital (TPC) outlay but would be paid systematically over the course of the 30-odd year program.

Details on the cost estimating are found in Appendix H.

4.1.4 Schedules

Schedule durations reflect the number of years needed before facility startup. Schedule durations have been developed by experience with analog facility projects throughout the DOE complex. The schedule required to build a vitrification or steam reforming facility is expected to be longer than a grouting facility because they are more complex and costly processes. Process complexity increases if a large number of systems, subsystems, and controls are required. High temperature processes include additional complexity due to offgas treatment challenges not inherent in low-temperature processes, such as grouting. The overall size and complexity of a facility for a vitrification or steam reforming process exceed those for a similar capacity grouting plant, driving both cost and schedule. Details on the schedule estimates are found in Appendix H.

4.1.5 Regulatory Compliance

A Performance Evaluation by the team has concluded that all three primary wasteforms can meet applicable DOE requirements for disposal at the IDF or WCS.

Vitrification and steam reforming are high temperature processes expected to destroy the nitrate and organics in the waste feed, so these constituents are not expected to be in the immobilized vitrification and steam reformed wasteforms. Pretreatment to destroy the organic species or deviations from the System Plan 8 feed selection may be required for grouting. This feed selection approach could involve routing potentially high organic content Low Activity Waste (LAW) to the Waste Treatment and Immobilization Plant (WTP) LAW process for vitrification and ensuring only low organic content LAW is fed to the SLAW grouting process. It is believed that viable pretreatment technologies are available to perform this treatment, but this could add technology development and complexity to the grouting option if changes in the feed selection are not pursued. This will need to be addressed for both IDF or WCS disposal options.

The wasteforms from all three technologies can meet interstate transportation requirements for shipment to WCS and can meet disposal waste acceptance criteria at WCS. Details on Regulatory Compliance are found in Appendix I.

Table 10 High-level comparison of the five representative cases for immobilization of Hanford SLAW per the analysis criteria specified in NDAA17

<table>
<tr><th>NDAA CRITERIA</th><th>VITRIFICATION CASE</th><th>GROUTING CASE I: DISPOSAL ONSITE AT INTEGRATED DISPOSAL FACILITY (IDF)</th><th>GROUTING CASE II: DISPOSAL OFFSITE AT WASTE CONTROL SPECIALISTS (WCS)</th><th>STEAM REFORMING CASE 1: SOLID MONOLITH PRODUCT TO IDF</th><th>STEAM REFORMING CASE 2: GRANULAR PRODUCT TO WCS</th></tr>
<tr><td>RISKS/ OBSTACLES*</td><td>• Most complex process
• Most dependent on integrated facility performance
o Highest throughput risk
o Most impacted by feed variability
o Lowest single-pass retention
• Highest volume and curies in secondary waste (dominant contributor to onsite releases)</td><td colspan="2">• Likely for organics subject to land disposal restrictions (LDRs) to remain in grouted wasteform, requiring mitigation measures, such as
o Waste pretreatment to destroy/remove LDR organics
o System Plan adjustments to allow only wastes without LDR organics to feed grouting process
• May require Tc treatment for onsite disposal
• Highest primary waste volume</td><td colspan="2">• Least technically mature for SLAW feed
• Complex process
• Requires rigorous process monitoring and control of fluidized bed and solid product handling system</td></tr>
<tr><td>BENEFITS</td><td>• Most technically mature for SLAW feed
• High temperature LDR organic/nitrate destruction
• Lowest primary waste volume</td><td colspan="2">• Least complex process
• Least dependent on integrated facility performance
o Lowest throughput risk
o Start/stop flexibility
• Ambient temperature process
o Minimal offgas treatment
o Worker safety
• Lowest secondary waste volume</td><td colspan="2">• High temperature LDR organic/nitrate destruction
• Does not appreciably increase waste volume during treatment
• Does not produce liquid secondary wastes (besides equipment decontamination, etc.)</td></tr>
<tr><td rowspan="3">COSTS** & SCHEDULES***</td><td>~$20 to ~$36B</td><td>~$2B to ~$3B</td><td>~$5B to ~$8B</td><td>~$6B to ~$12B</td><td>~$9 to ~$17B</td></tr>
<tr><td>10-15 years</td><td>8–13 years</td><td>8–13 years</td><td>10-15 Years</td><td>10-15 Years</td></tr>
<tr><td>• Highest cost</td><td colspan="2">• Lowest cost
• Cost and schedule estimates informed by SRS Saltstone operation</td><td colspan="2">• Lower cost high temperature treatment option to meet BDAT for organics and destroy nitrates
• Training and development (T&D) costs due to maturing technology to TRL>7
• Operating expense (OPEX) / life cycle cost also impacted by maturity
• Transport and disposal costs significant but not dominant portion of total cost
• Cost and schedule estimates informed by INL IWTU design, demo, and startup.</td></tr>
<tr><td>REGULATORY COMPLIANCE****</td><td>• Primary wasteform meets DOE Technical Performance Criteria (TPC) for onsite disposal (IDF)
• Meets state permit requirements for primary wasteform
• I-129 secondary waste may require mitigation
• Secondary wastes meet out-of-state WAC requirements</td><td>• High likelihood for primary wasteform to meet DOE TPC for onsite disposal (IDF) (e.g., DOE 435.1) based on Cast Stone data
• Need for additional validation/ demonstration of acceptable wasteform performance for onsite disposal</td><td>• Compliant (assuming LDR organics are addressed for offsite transport and disposal at WCS</td><td>• High likelihood for primary monolith wasteform to meet DOE TPC for onsite disposal (IDF)
• High likelihood to meet state permit requirements
• Need for additional validation/ demonstration of acceptable wasteform performance for onsite disposal</td><td>• Compliant for off-site transport and disposal at WCS</td></tr>
</table>

**All technologies require significant concurrent Line Item and operations funding (> $1.5B/year)*

***Lifecycle costs are shown. SLAW capital expenses will occur at the same time as other WTP and Tank Operations Contract capital projects such that the overall projected costs of all concurrent projects and operations will be greater than 2 times the current $1.5B/year regardless of SLAW costs. This is a cross-cutting programmatic risk.*

****The window to startup of any Hanford SLAW immobilization facility is 15 years to meet a 2034 startup; the time required to complete construction and startup of the facilities are shown.*

*****All wasteforms are compliant for out-of-state transport and disposal. Secondary grouted wasteform & onsite disposal permit pending.*

APPENDIX A. PRETREATMENT

A.1 ASSUMPTIONS

In all cases it is assumed that the feed vector will undergo treatment to remove Cs and be filtered to remove any suspended solids prior to SLAW pretreatment. In this analysis pretreatment beyond the planned treatment to remove Cs and suspended solids is only considered for the grout immobilization option. Data would indicate that some portion of the feed vector will require pretreatment to address LDR organics prior to grouting. Additional pretreatment operations have been evaluated as mitigation steps to remove I, Tc, or LDR metals on an as needed basis to allow the alternative grout wasteform to be accepted. In addition, removal of Sr was identified as an opportunity that could reduce disposal costs at off-site facilities.

The sections in this appendix provide bases for use in several cases describing need for pretreatment.

A.2 REQUIREMENTS

A.2.1 LDR Organics

Significant characterization of radionuclides and inorganics in the liquid and solid phases of the tank waste has been conducted and is continuing, however, there is much more limited data on presence and concentration of LDR organics in the SLAW feed. Hanford tanks are suspected of containing a wide range of LDR organics, as documented in the Part A RCRA Permit for both SSTs and DSTs. Establishing a firm removal requirement for either the LDR organics or metals is problematic at this point in time based on the current level of underlying characterization of the feed vector. Total organic carbon is used in the BBI to show the amount of organic species present in the waste. Recent organics characterization of a very limited set of tank waste samples has identified some LDR organics, but most at very low levels, and this limited data cannot be extended to the broader set of tanks. There is, however, a more robust set of organics data from headspace and tank farm exhauster stack emissions sampling. This data can be used to estimate the maximum potential organic content in the tank liquid wastes by converting maximum tank headspace and exhauster measurements of all LDR organics actually detected in historic sampling to liquid waste concentrations using Henry's Law Constants for each organic. This approach should be considered a screening-level analysis, designed to assess whether there was a potential for LDR organics to greatly exceed LDR total waste standards that would indicate treatment was required. The results are shown in Table A.1. Based on this approach:

- 114 relevant LDR organics that are known or suspected to be present in tank waste based on results of a regulatory data quality objectives process
- 61 of these LDR organics have been detected in tank headspace or tank farm exhausters above detection levels
- 22 of these LDR organics have the highest potential to exceed LDR total waste standards, based on approximate tank waste concentrations estimated from maximum vapor concentrations in one or more of the tanks.

The results shown in the third column (the one with the "Henry's Law" in the header) of the Table A.3 are not representative of any single tank but an aggregate of the highest reported values across all tanks. A similar approach was taken for AW-106 sampling data. The exceedance of the LDR standard based on measured organics in the liquid waste that were above the analytical reporting limit only are shown in the fourth column only N-methyl-N-nitroso methanamine, (CAS#62-75-9) exceeded the Total Waste Standard. It should also be noted that in many cases the analytical reporting limit itself was higher than the LDR standard. In the last column [AW-106 NR for non-report] presents the estimated exceedance if the organic compound was assumed to be actually present at the analytical reporting limit concentration. In this case a number of additional compounds could have exceeded the LDR standard.

Based on this screening approach, prudent planning would assume that for a least some portion of the feed vector, some pretreatment would be required to reduce the organic content if the immobilization process does not destroy organic species. The extent of removal for the purposes of this analysis is assumed to be 50 to 99.95%.

Table A.1. Potential LDR Organic in Exceedance of Total Waste Standard

		Henry's Law	**AW-106 R**	**AW-106 NR**
Chemical Name	**CAS Number**	**Exceedance of Total Waste Standard (from Max Headspace Vapor Conc.) (Cmax / Cstd)**	**Exceedance of Total Waste Standard (Cmax / Cstd)**	**Exceedance of Total Waste Standard based on reporting / detection limits (Cmax / Cstd)**
Propane, 2-nitro-	79-46-9	N/A*		
Phenol	108-95-2	2060	0.000	**23.0**
1,2-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	117-81-7	1140	0.000	1.16
Ethanone, 1-phenyl-	98-86-2	687	0.000	0.00
Phenol, 2-methyl-	95-48-7	483	0.000	8.50
1,2-Benzenedicarboxylic acid, diethyl ester	84-66-2	235	0.000	2.67
Morpholine, N-nitroso-	59-89-2	137	0.000	2.01
2-Propanone	67-64-1	126	0.105	0.00
Methanamine, N-methyl-N-nitroso-	62-75-9	113	**4.530**	2.30
2-Butanone	78-93-3	104	0.035	0.00
1-Butanol	71-36-3	95.9	0.000	0.73
Pyridine	110-86-1	75.5	0.000	77.10
Methanol	67-56-1	49.1	0.000	0.00
Acetic acid ethyl ester	141-78-6	40.4	0.000	0.01
Propanenitrile	107-12-0	34.1	0.000	0.00
Acetonitrile	75-05-8	7.6	0.000	0.00
1-Propanol, 2-methyl-	78-83-1	5.5	0.000	0.29
Dichloromethane	75-09-2	5.1	0.000	0.01
2-Pentanone, 4-methyl-	108-10-1	4.9	0.000	0.03
9H-Fluorene	86-73-7	2.1	0.000	13.60
2-Propenal	107-02-8	1.5	0.000	0.00
1-Propanamine, N-nitroso-N-propyl	621-64-7	1.5	0.000	2.50

For the RCRA listed metals, some (e.g., silver and barium) are supplemental analytes in the BBI, and information on amounts of these metals in the waste is not available for all tanks. Like organic treatment, it is prudent to assess removal of RCRA metals from the feed stream or complexation within the wasteform for selected wasteforms. It is assumed that 50 to 90% removal or complexation would be sufficient to allow the immobilized waste to pass TCLP for this evaluation. It is just not known if an individual tank or batch-specific conditions would require additional pretreatment to assure that final wasteform would meet LDR requirements.

A.2.2 LDR Metals

For the RCRA listed metals, some (e.g., silver and barium) are supplemental analytes in the BBI, and information on amounts of these metals in the waste is not available for all tanks. Like organic treatment, it is prudent to assess removal of RCRA metals from the feed stream or complexation within the wasteform for selected wasteforms.

A.2.3 Technetium

The removal of technetium (Tc) is part of a potential mitigation strategy to be employed as needed to ensure that the SLAW grout meets the onsite disposal performance goals. The basis for the technetium (Tc) removal is the 2017 Integrated Disposal Facility (IDF) Performance Assessment (PA). The underlying assumptions are that:

- Liquid Secondary Waste (LSW) grout is conservative relative to performance of a grouted SLAW wasteform.
- LSW performance extrapolation is linear to much higher Tc inventories.
- Fractional split of Tc inventory between LAW and SLAW is 50%.

Based on these assumptions and a maximum groundwater limit of 900 pCi/L to meet regulatory requirements, an overall Tc removal of ~92% would be required for a low performing grouted wasteform. To limit the groundwater concentration to 100 pCi/L, an overall Tc removal of ~99% would be required. It should be noted that these values are based on early assessment of the potential need for pretreatment and are not reflective of the performance shown in the PE conducted as part of the FFRDC review. The PE has shown that Tc removal is not required to meet requirements for high performing grouts. See Appendix F.
It should be noted that the performance of ILAW grout formulation may be significantly better than the LSW grout; with regards to Tc retention, therefore, the required pretreatment evaluated is assumed to be conservative.

A.2.4 Iodine

The basis for the iodine (I) removal is the 2017 IDF PA and was determined in a similar manner. It was assumed that the fraction of I inventory to be sent to SLAW is 50% of that to be sent to WTP.

Based on these assumptions and a maximum groundwater limit of 1 pCi/L to meet regulatory requirements, an overall iodine removal of ~50% would be required for a low performing grouted wasteform. To limit the groundwater concentration to 0.05 pCi/L, an overall I removal of ~97% would be required.

Again, it should be noted that these values are based on early assessment of the potential need for pretreatment and are not reflective of the performance shown in the PE conducted as part of the FFRDC review. The PE has shown that I removal is not required to meet requirements for high performing grouts. See Appendix F.

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A.2.5 Strontium

The removal requirements for Sr, if determined to be needed to support the Grout Case II Opportunity variant that would change the classification of the resulting waste, are based on providing a significant degree of waste reclassification to justify the additional processing cost. Data on the Feed vector was available on a monthly basis and was analyzed in that form (additional data on the feed vector is presented in appendix L). As shown in Table A.2, grouting the base-line feed vector with no Sr removal, will result in the waste being classified as Class C for 33 of the 441 months with the balance being classified as Class E. The TRU content of the Feed Vector during those 33 of the months is the driving factor resulting in the classification as Class C waste. Removal of

90% to 95% Sr from the waste stream only reduces the amount of Class B waste produced by 17-23%, (408 months of class be are reduced to 338 and 314 months respectively and 70 or 94 months becoming Class A waste) whereas 99% Sr removal shifts 99.5% of the months of Class B waste to Class A. Table A.3 provides a similar analysis for vitrified or Steam Reformed waste packages, however the application of Sr removal for these waste processing technology cases are not considered within the five cases analyzed.

Table A.2. Impact of Sr removal on Waste Classification for Grout

Grout (1770 kg/m3, all nuclides retained and 1.8 multiplier)					
% Sr-90 removal	GTCC (months)	Class C (months)	Class B (months)	Class A (months)	Notes
None	0	33	408	0	TRU from WTP PT cause Class C
90% removal	0	33	338	70	
95% removal	0	33	314	94	
99% removal	0	33	2	406	

Table A.3. Impact of Sr removal on Waste Classification for vitrified or Steam Reformed Waste

Glass or Steam Reformed (2600 kg/m3, all nuclides and 1.0 multiplier)					
% Sr-90 removal	GTCC (months	Class C (months)	Class B (months)	Class A (months)	Notes
None	0	42	399	0	TRU from WTP PT cause Class C
90% removal	0	42	399	0	
99% removal	0	42	1	398	

It should be noted that the strontium concentrations in the SLAW feed vector may not be within a factor of 2 of the actual concentrations [Pierson, 2012]. The amount of soluble strontium in the supernate as predicted by the TOPSim model is based on the Integrated Solubility Model (ISM). ISM was shown to poorly predict soluble Sr concentrations (and, in turn the Sr-90 concentrations) during saltcake dissolution studies. Thus, the amount of strontium removal required could be less than assumed; however, it is likely the amount of soluble Sr-90 would still require some treatment to allow the waste to meet Class A requirements.

It is noted that the ion exchange resin for cesium removal during DFLAW has been changed from spherical resourcinol-formaldehyde (sRF), an elutable resin, to Crystalline Silico-Titanate (CST), a non-elutable resin [Oji, et al., 2012]. CST will sorb some of the soluble Sr; additional research is required to better understand the amount of Sr removal expected. Thus, the need for Sr removal could be decreased by the changes to the cesium removal process during DFLAW.

Finally, it is noted that a process has been developed and is planned for use in the tank farms to reduce soluble Sr and TRU from tanks AN-102 and AN-107. This process will add strontium nitrate to the tank to force most of the Sr-90 to precipitate along with the stable Sr. The concentration of total strontium in the supernate is increased, but the amount of Sr-90 is decreased by isotopic dilution. This process will be followed by a sodium permanganate strike to precipitate TRU species. System Plan 8 [2017] and the feed vector from the Integrated Flowsheet [L. W. Cree, et al, 2017] already account for these processes for these tanks.

A.3 SELECTED PRETREATMENT TECHNOLOGIES

A.3.1 LDR Organics/Metals

A.3.1.1 LDR Organics

For use with the grout option, a relatively low temperature oxidation is proposed. There are several organic management methods that could be applied. These include Chemical Oxidation (CHOXD) and Recovery of Organics (RORGS). CHOXD is often accomplished with the addition of peroxides, permanganate, or ozone.

Peroxide: Chemical oxidation processes are commonly used to treat industrial waste water to reduce odours, decolourizes effluent, destroy organic matter and improve precipitation and flocculation could also to treatment radioactive liquid waste (Kidd and Bowers, 1995). Addition of liquid hydrogen peroxide (H_2O_2) in the presence of ferrous iron (Fe^{2+}) produces Fenton's Reagent which yields free hydroxyl radicals ($\bullet OH$). Ferric sulfate is added after hydrogen peroxide. The ferric sulfate serves as a flocculant and destabilizes the charge around the precipitate that will be formed later. In the work described by Kidd and Bowers (1995) sodium hydroxide is added to precipitate the metals. Usually the precipitation will be carried out at a pH of 9.0, but high radioactivity concentrations are reduced more efficiently at higher a pH (usually around 12). This is followed by the addition of carbon and filtration. This process also removes a significant fraction of the metals such as barium, chromium, lead, mercury, etc. A significant drawback is the potential increase in liquid volume due to the volumes of hydrogen peroxide required (Nardi, 1989).

Potassium permanganate: Wet oxidation is a technique for breaking down organic materials into carbon dioxide and water leaving stable inorganic residue compatible with direct disposal or via cement encapsulation. El-Dessouky et al. (2001) conducted tests on spent organic waste tributyl phosphates and diluents using permanganate ($KMnO_4$). They found that 0.1 N or higher $KMnO_4$ concentrations could result in 88 to 99.9% degradation of all the compounds tests. Reaction times of 6 hours or greater and temperatures of 90 to 100 C were also required to achieve high degradation.

Ozone: Ozone is one of the strongest oxidizing agents that can used to interact with organic liquids. The structure of ozone is such that an oxygen atom can easily be detached, yielding a free oxygen radical to interact with the organic material (Horvath et al., 1980). The reaction mechanism of ozone with organic substances can be via radical or an electrophyllic / nucleophyllic attack. Ozone can be easily produced on demand from dry air or oxygen using an electric field to generate corona discharges between electrodes. Like peroxide oxidation, ozone reactions are effective in systems with a neutral or alkaline pH. Work conducted by Klasson, (2002) showed that the rate of disappearance of extractable organic compounds in produced water was first-order with respect to the ozone and extractable concentrations. The rate data also suggested that there are several competing reactions involving ozone and that some of these reactions proceed at a faster rate (in the order of minutes). However, some of the reactions do not initially occur but occur only after prolonged exposure to ozone. The result is an overall slow rate (in the order of hours) of destruction of extractable organics. Degradation rate constants were higher at 80°C compared 22°C and the ozone demand was approximately half at the higher temperature.

Hitachi has developed a system that decomposes organic impurities in laundry and shower drains by applying ozone (Fukasawa, et al., 2001). While not directly applicable the problem at hand, the recirculation loop / ozone injection system could potential be scaled up.

RORGS includes the use of carbon adsorption, liquid / liquid extraction and physical phase separation or centrifugation. None of these methods appear to be attractive for this application.

For this application, the addition of permanganate is proposed as a primary means and ozone is proposed if additional oxidation is required. Care must be taken relative to the addition of excess permanganate if subsequent processing steps require the use of chemical reductants to be effective.

A review of the available literature into the reactivity of the 22 LDR organic compounds identified by the scoping analysis shown in Table A.1 is presented in Table A.4.

It should be noted that data on the effectiveness of chemical oxidation with either permanganate or ozone were not found for all the potential compounds requiring treatment. Many of these compounds will be at least partially oxidized by ozone or permanganate. Partial oxidation, such as the conversion of alcohols or aldehydes to carboxylic acids, will not necessarily reduce the toxicity of the compounds. Nitrated aliphatic compounds, such as 2-nitro-propane, and ketones, such as 2-butanone, will not generally react. Additional R&D will be required to evaluate the effectiveness of chemical oxidation with either permanganate or ozone where data is not available and to confirm the effectiveness at the expected levels and chemical matrix. It is anticipated that there will be some cases where the chemical oxidation will not be effective or effective enough. In these cases, the mitigation could be to swap the effected tank intended for SLAW with one planned for first LAW and thereby performing thermal treatment on the effected waste stream. Also, it is important to note that in many cases the oxidation does not reduce the compound all the way to CO2, NOx, etc., but results in the formation if intermediary compounds.

As noted previously not all these compounds are present in all tanks. In addition, the possible levels shown in Tables A.1 and A.4 are based on the highest observed levels across all tanks and all sampling periods. These represent the worst of the worst cases. In the case of AW-106 only N-methyl-N-nitroso-methanamine was present at levels requiring treatment. While the exceedance is only 4.53 time the concentration-based standard there was no chemical oxidation effectiveness data found. This level of exceedance would require ~82% destruction.

Typically, oxidation of organic molecules by $KMnO_4$ will proceed until the formation of carboxylic acids. Therefore, alcohols will be oxidized to carbonyls (aldehydes and ketones), and aldehydes will be oxidized to carboxylic acids (LibreText, 2015). In general, normal ketones are not oxidized except under extreme conditions. At high temperature, ketones are cleavage oxidized by a strong oxidizing agent like $KMnO_4$. An exception is a benzylic carbonyl group, which $KMnO_4$ oxidizes easily (WikiPremed, 2016).

A quick summary of general KMO_4 chemistry can be found in LibreText (2015) –

$KMnO_4$ is able to oxidize carbon containing compounds if the carbon bonds are sufficiently weak. These would include compounds with:

1. Carbon atoms with π bonds, as in alkenes and alkynes
2. Carbon atoms with weak C-H bonds, such as
    - C-H bonds in the alpha-positions of substituted aromatic rings
    - C-H bonds in carbon atoms containing C-O bonds, including alcohols and aldehydes
3. Carbons with exceptionally weak C-C bonds such as
    - C-C bonds in a glycol
    - C-C bonds next to an aromatic ring AND an oxygen

$KMnO_4$ will also oxidizes phenol to para-benzoquinone.

Examples of organic compounds that are not oxidized include:

a) Aliphatic carbons (except those alpha to an aromatic ring, as above)

b) Aromatic carbons (except phenol, as above)
c) Carbons without a C-H bond, except as in (3) above.

While references for the oxidation of many of the 22 compounds could be found, most if not all were studied under significantly different conditions than would associated with the feed vector and considerable additional R&D should be conducted under the relevant conditions. The following text and table summarize the reactions of individual LDR organics with permanganate or ozone:

- **2-nitro-Propane** – Does not react with ozone or permanganate.
- **Phenol -** Phenol reacts with ozone to form several intermediates, which eventually turn into CO_2. Phenol reacts with permanganate to form ortho and para-di benzoquinones.
- **1,2-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester and 1,2-Benzenedicarboxylic acid, diethyl ester (Diethyl phthalate) -** Permanganate should oxidize the ester bonds under acidic condition (Jung, et al., 2010). It has been reported by Oh, et al.,(2006) that ozone was effective in removing up to 70% from water. The efficiency of removal is dependent on pH, with removal of ~70% at neutral pH and < 20% at a pH of 4.
- **Ethanone, 1-phenyl** - Does not react with ozone. Reacts with permanganate to form benzoic acid and methanoic acid.
- **Phenol, 2-methyl** - Should react similarly to phenol
- **Morpholine, N-nitroso** - Converted into N-nitroso-2-hydroxymorpholine by permanganate (Manson, et al., 1978). Ozone also reacts with morpholine (Tekle-Röttering, et al., 2015)
- **Methanamine, N-methyl-N-nitroso- (Dimethyl nitrosamine)** - Reacts with strong oxidizers (National Center for Biotechnological Information, 2019, Lee, et al., 2007).
- **2-Butanone** - No reaction with secondary ketones. (Chemistry, LibreTexts,)
- **1-Butanol** - Oxidized to butanoic acid – (Chemistry, LibreTexts)
- **Pyridine** - No reaction - Pyridine is uses as a solvent for reacting other organics with permanganate (Yasue and Kato, 1960)
- **Methanol** - Permanganate will oxidize to formic acid. A number of references can be found on the vapor phase ozone oxidation of methanol using V_2O_5 catalyst such as that by (Sahle-Demessie and Devulapelli, (2009).
- **Acetic acid ethyl ester** - Permanganate likely to oxidize to two acetic acid molecules.
- **Propanenitrile** - No references found. Probably no reaction, like with acetonitrile.
- **Acetonitrile** - Does not normally react with permanganate and is used as a solvent for reactions with other compounds.
- **1-Propanol, 2-methyl** - Reaction with ozone or permanganate would give 2-methyl 1-propanoic acid.
- **Dichloromethane** - No reaction expected. Dichloromethane has been report to be used as a solvent to study the oxidation kinetics of C4-C10 aliphatic aldehydes by solubilized permanganate (Holba et al, 1998) (Chemistry Stack Exchange, 2012)
- **2-Pentanone, 4-methyl** - The kinetics of the oxidation of 2-Pentanone by a potassium permanganate is first order and increases as $[OH^-]$ increases. (D.F. Latona, 2016.)
- **9H-Fluorene** - potassium permanganate in alkaline medium at 25°C reacts with 9H-Flourene to produce 9H-Fluorene-9-one. (Fawzy, et al., 2016.)
- **2-Propenal** - No reaction at room temperature. Will react with permanganate at high temperature to give acetic and formic acids.
- **N-nitroso-N-propyl-1-Propanamine** - Destruction of N-nitrosamines in lab wastes using potassium permanganate was described (IARC, 1982)

Table A-4 Reactivity of Selected LRD Organics to Permanganate and O-Zone

		Henry's Law	**Permanganate**	**Ozone**
Chemical Name	**CAS Number**	**Exceedance of Total Waste Standard**	**Notes from the literature would indicate the following**	**Notes from the literature would indicate the following**
Propane, 2-nitro-	79-46-9	N/A[45]	Not reactive	Not reactive
Phenol	108-95-2	2060	Form ortho and para-di benzoquinones	Reacts to form some intermediaries
1,2-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	117-81-7	1140	Should oxidize ester bond under acidic conditions	Reported to remove 70% from water
Ethanone, 1-phenyl-	98-86-2	687	Forms benzoic acid and methanoic acid	Not reactive
Phenol, 2-methyl-	95-48-7	483	Similar to phenol	Similar to phenol
1,2-Benzenedicarboxylic acid, diethyl ester	84-66-2	235	Should oxidize ester bond	No reference found
Morpholine, N-nitroso-	59-89-2	137	Converted into N-nitroso-2-hydroxymorpholine	Oxidizes morpholine
2-Propanone	67-64-1	126	Not reactive	Not reactive
Methanamine, N-methyl-N-nitroso-	62-75-9	113	Reacts with strong oxidizers	Reacts with strong oxidizers
2-Butanone	78-93-3	104	Not reactive	Not reactive
1-Butanol	71-36-3	95.9	Oxidized to butanoic acid	Oxidized to butanoic acid
Pyridine	110-86-1	75.5	Not reactive	--
Methanol	67-56-1	49.1	Oxidizes to formic acid	Oxidation with V_2O_5 catalyst
Acetic acid ethyl ester	141-78-6	40.4	Likely to oxidize to two acetic acid molecules	--
Propanenitrile	107-12-0	34.1	No ref found, probably not reactive.	No ref found, probably not reactive.
Acetonitrile	75-05-8	7.6	Not reactive	Not reactive
1-Propanol, 2-methyl-	78-83-1	5.5	Forms 2-methyl 1-propanoic acid	Forms 2-methyl 1-propanoic acid
Dichloromethane	75-09-2	5.1	Not reactive	Not reactive
2-Pentanone, 4-methyl-	108-10-1	4.9	Should react	--
9H-Fluorene	86-73-7	2.1	Reacts to form 9H-Fluorene-9-one	--
2-Propenal	107-02-8	1.5	No reaction at room temp. Reacts at high temp to form acetic and formic acids	--
1-Propanamine, N-nitroso-N-propyl	621-64-7	1.5	Should react. Destruction of N-nitrosamines in lab wastes has been reported	No ref found, probably will react

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[45] 2-nitro-propane has treatment-based standard rather than concentration-based standard.

A.3.1,2 LDR Metals

Bhattacharyya, et al. (2006) found that sulfide precipitation with Na_2S to be highly effective to achieve a high degree of separation of heavy metal cations (Cd, Zn, Cu, and Pb) and of the oxyanions of arsenic and selenium from complex wastewaters. These separations were evaluated with a dilute synthetic mixture and with actual copper smelting plant wastewater. They were able to achieve removals of Cd, Zn, and Cu from the actual wastewaters of greater than 99%, and As and Se removals of 98 and >92%, respectively. Cd, Cu, and Zn concentrations in the range of 0.05 to 0.1 mg/1 were achieved with sulfide precipitation. The use of sulfide precipitation resulted in metal separations and settling rates considerably higher than those obtained with conventional hydroxide precipitation (lime).

A.3.2 Technetium

A.3.2.1 Solvent Extraction

Work reported by Chaiko, et al. (1995) examined the use of aqueous biphasic extraction systems based on the use of polyethylene glycols (PEGS) for the selective extraction and recovery of long-lived radionuclides, such as ^{129}I, ^{75}Se, and ^{99}Tc, from caustic solutions containing high concentrations of nitrate, nitrite, and carbonate. In this approach the anionic species such as I^- and TcO^-_4 are selectively transferred to the lighter PEG phase. The reported partition coefficients for a wide range of inorganic cations and anions, such as sodium, potassium, aluminum, nitrate, nitrite, and carbonate, are all less than one.

Bruce Moyer's (Moyer, et al., 1999) group at ORNL developed a process (SrTalk) for removing Sr and Tc from wastewater in the late '90s. The Sr part did not work well in high alkalinity, but the Tc part worked well. A 12-stage SRTALK flowsheet was developed using a solvent consisting of 0.04 M $DtBuCH_{18}C_6$ and 1.8M TBP in Isopar® L (1:1 v:v TBP: Isopar® L). Test were conducted in 2 cm centrifugal contactors. The scrub section employed, 0.5 M NaOH and stripping was accomplished with 0.01 M HNO_3. The centrifugal-contactor test performed as designed, demonstrating the clean separation of Tc from the bulk waste constituents, especially sodium. The Tc was concentrated by a factor of 9.9 with a DF of 10.7, and the sodium concentration was reduced by a factor of 5800 to 0.0010 M in the strip solution.

A.3.2.2 Ion Exchange

The review of pretreatment technologies conducted by Wilmarth, et al. (2011) that addressed both Sr removal also addressed Tc removal. They note that technetium-99 is, in most cases, present in the supernatant liquid as the pertechnetate ion (TcO_4^-). They state that it is possible to remove this radionuclide through a number of processes, such as ion exchange, solvent extraction, crystallization, or precipitation with ion exchange been studied to the highest degree. DOE conducted extensive testing of commercial and developmental ion-exchange materials in the early 1990's to determine suitable materials for separating various radionuclides from Hanford Site tank waste solutions. Table A.5 from that report lists batch-distribution values for sorption of Tc from a simulated high-organic tank waste for the most promising materials examined at that time. It should be noted that SuperLig® 639 resin was not being manufactured at the time the TWRS program conducted these tests.

WTP project conducted extensive testing of SuperLig® 639 in the late 1990s and 2000's. These tests included repetitive loading and elution of the ion-exchange resin and loading and elution profiles. Chemical and radiation stability testing of SuperLig® 639 resin has also been conducted and a preliminary ion-exchange model was developed.

Table A.5. Batch distribution ratios (Kd) for sorption of Tc from a Hanford Tank Waste Simulant containing organic complexants (Wilmarth, et al., 2011)

Ion exchanger	Description	*Kd*, mL/g[a]
Purolite A-520E	Macroporous anion exchanger with triethylamine groups	1,300
Ionac SR-6	Macroporous anion exchanger with tributylamine groups	1,170
Reillex HPQ	Copolymer of 1-methyl-4-vinylpyridine and divinylbenzene	670
n-butyl-Reillex HP	*n*-butyl derivative of poly-4-vinylpyridine/divinylbenzene (Reillex^{TM} HP)	1,405
iso-butyl-Reillex HP	iso-butyl derivative of Reillex^{TM} HP	810
n-hexyl-Reillex HP	*n*-hexyl derivative of Reillex^{TM} HP	1,405
n-octyl-HP	*n*-octyl derivative of Reillex^{TM} HP	780
TEVA·Spec	Methyltricaprylammonium chloride (Aliquat^{TM} 336) sorbed onto an acrylic ester nonionic polymer	1,280
Alliquat 336 beads	Aliquat^{TM} 336 sorbed onto porous carbon beads (Ambersorb^{TM} 563)	1,420

[a] In most cases, the simulant contained 3.45 M Na, 0.37 M Al, 0.0062 M Cr, and 0.71M total organic carbon (originally added as EDTA). The pH was reported as 13.7. For the TEVA·Spec and iso-butyl-Reillex HP measurements, the simulant composition was 2.2 M Na, 0.16 M Al, 1.0 M total organic carbon (Cr was not reported). In the latter case, the pH was reported as 13.2.

Tests by Burgeson, et al. (2005) with SuperLig® 639 ion exchange resin manufactured by IBC Technologies were conducted using a dual-column configuration, each containing a 5-mL resin bed for four Hanford tank supernates. Two tank-waste supernates exhibited a high fraction of nonextractable technetium (nonpertechnetate): AN-102/C-104 was 50% nonpertechnetate, and AP-104 was 69% nonpertechnetate. The pertechnetate removal for all tested supernates, showed an average of 99% removal for supernates that were essentially all pertechnetate and 86% removal for supernates that contained a high fraction of nonpertechnetate. The column elution was conducted using 65°C water and resulted in 99% elution on average within 16 bed volumes of eluant.

A report on “Recommendation for Supplemental Technologies for Potential Mission· Acceleration” by Gasper, et al. (2002) recommended that technetium be removed from the dissolved saltcake waste using SuperLig 639 resin.

Gasper, et al. also state:
The valence state of the soluble technetium in the Hanford Site tank wastes is predominantly +7, with technetium present as the pertechnetate (TcO^-_4) anion. SuperLig 639 resin is capable of only removing technetium present as the pertechnetate anion. Batch contact and laboratory-scale ion exchange column tests have indicated that 1 to 5 percent of the technetium present in samples of non-complexed tank wastes is not present as the pertechnetate anion and cannot be extracted using SuperLig 639 resin (WSRC-MS-2001-00573)

But ultimately, it was determined that the ^{99}Tc ion-exchange process would not be implemented in the Hanford WTP because the performance assessment for the LAW disposal site found it to be unnecessary for the safe disposition of the waste (Wilmarth, et al., 2011).

A.3.3 Iodine

Iodine removal from tank waste supernates has not been evaluated to the extent of other radionuclides. Selected laboratory studies were found using silver absorbents, as described below, but these studies represent work at very low TRL levels. If iodine removal is determined to be required, extensive R&D will be required to develop and mature the technology needed.

Kim, et al. (2017) have reported on some very recent work on the removal of radioactive iodine from alkaline solutions containing fission products. Their target goal to be practically applicable was to achieve a decontamination factor of at least 200. Their sorbent was an alumina doped material containing with silver nanoparticles (Ag NPs). They were able to achieve iodine removal and recovery efficiencies of 99.7%.

Laboratory tests also have been conducted recently by Asmussen et al.[46], using several Ag-containing materials as immobilization agents, or "getters", for iodine removal from deionized (DI) water and a liquid Hansford LAW simulant. These getter materials included Ag impregnated activate carbon (Ag–C), Ag exchanged zeolite (Ag–Z), and argentite. In the anoxic batch experiments with LAW simulant, Ag–Z vastly outperformed the other getters with Kd values of 2.2×10^4 mL/g at 2 h, which held steady until 15 days, compared with 1.8×10^3 mL/g reached at 15 days by the argentite. Asmussen et al.[47], also conducted batch sorption experiments using silver-functionalized silica aerogels remove iodine from both deionized water (DIW) and various Hanford Site Waste Treatment Plant (WTP) off-gas condensate simulants. These batch tests ran for periods as long as 10 days and were challenged with iodine concentrations of 5 to 10 ppm as iodide (I^-) or iodate (IO_3^-). They found in batch test that for neutral, less-complex systems, the sorbent rapidly removed the I^- from the solution and showed preferential removal of I^- over Br^- and Cl^-. They also showed that the silver-functionalized silica aerogels were able to remove IO_3^- but at a slower rate than for I^-.

A.3.4 Strontium

A number of options have been identified for the removal of Sr from alkaline waste. These include both solvent extraction and ion exchange technologies.

A.3.4.1 Solvent Extraction

D2EHPA based strontium removal: A method based on Di-2-ethyl hexyl phosphoric acid (D2EHPA) acting as a carrier in liquid membrane or as an extractant in simultaneous extraction-re-extraction for Sr removal from strong alkaline solutions in the presence of 1M NaOH and 3M NaNO, has been developed by Kocherginsky, et al. (2002). Using liquid extraction-re-extraction, 98% of Sr was removed at a rate of $4.5x10^{-9}$ mol-s^{-1}-L^{-1}.

Caustic-Side Solvent Extraction (CSSX): The combined extraction of cesium and strontium from caustic wastes has been studied at ORNL by Delmau, et al. (2006). This combined extraction is conducted by the addition of a crown ether, 4,4'(5')-di(tert-butyl)cyclohexano-18-crown-6, and a carboxylic acid to the Caustic-Side Solvent Extraction (CSSX) solvent. This process has been tested using simulants and batch extractions.

A.3.4.2 Ion Exchange

Sylvester, et al., (1999) evaluated several inorganic ion-exchange materials for the removal of strontium from two simulated Hanford tank wastes (NCAW and 101SY-Cs5) using static batch experiments. Of the materials evaluated:

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[46] Asmussen, R. M., J.J. Neeway, A.R. Lawter, A. Wilson, N. Qafoku, Silver based getters for 129-I removal from low activity waste, Radiochim Acta 104 (12) (2016) 905–913, DOI 10.1515/ract-2016-2598.

[47] Asmussen, R.Matthew., Josef Matyáš, Nikolla P. Qafoku, Albert A. Kruger, Silver-functionalized silica aerogels and their application in the removal of iodine from aqueous environments, Journal of Hazardous Materials (2018), https://doi.org/10.1016/j.jhazmat.2018.04.081.

"sodium titanium silicate, $Na_2Ti_2O_3SiO_4 \cdot 2H_2O$ (NaTS), was the best material in NCAW with a *K*d of 2.7 x 10^5 mL/g at a volume-to-mass ratio of 200:1. In the 101SY-Cs5 simulant, strontium extraction was more difficult due to the presence of complexants and consequently *K*ds were greatly reduced. Sodium nonatitanate, NaTi, performed best in the presence of these complexants and gave a *K*d of 295 mL/g, though none of the materials performed particularly well. Both the sodium titanate and the sodium titanosilicate performed better than IONSIV IE-911, a commercially available ion exchanger, in the NCAW simulant, and consequently could be used for the removal of ^{90}Sr from highly alkaline tank wastes."

Monosodium Titanate: Wilmarth, et al. (2011) conducted a review of pretreatment technologies that addressed both Sr removal as well as Tc removal. This report discusses the removal requirements and differences between Hanford and SRS. They indicate that pretreating LAW before immobilization (either as saltstone or borosilicate glass) requires the removal of ^{137}Cs as well as other radionuclides to include, the TRU elements and ^{90}Sr. The waste incidental-to-reprocessing documentation at Hanford indicated that the TRU content of the LAW glass must be less than 100 nCi/g. They indicate that only the complexant concentrate wastes (from tanks 241-AN-102 and 241-AN-107) need ^{90}Sr and TRU removal but for purposes of altering the resulting waste classification significantly larger fractions of the feed vector will require treatment.

Monosodium titanate (MST) has been selected for the removal of TRU and Sr from the Savannah River waste whereas treatment with permanganate and nonradioactive strontium nitrate is the method of choice for the Hanford tanks 241-AN-102 and 241-AN-107 that contain high levels of organic complexants that render a process based on MST ineffective (Wilmarth, et al., 2011)

MST was developed at Sandia National Laboratory (SNL) in the 1970's as an inorganic sorbent material that exhibits high selectivity for strontium and actinide elements in the presence of strongly alkaline and high-sodium salt solutions. The Savannah River Site selected this material for ^{90}Sr and plutonium removal from HLW solutions in the early 1980s as part of what was referred to as the In-Tank Precipitation (ITP) process (Wilmarth, et al., 2011). In 2001, DOE selected MST for the strontium/actinide separation step within the SWPF. Subsequently, MST was selected for use in the Actinide Removal Process (ARP) to treat waste solutions low in cesium activity. Strontium removal is very rapid, whereas sorption of the plutonium and neptunium occurs at slower rates from the strongly alkaline and high-ionic-strength waste solutions.

MST has been successfully deployed in the ARP at the Savannah River Site. Recent results from SRNL on a modified version of monosodium titanate show promise to reduce contact times for the strontium and TRU removal.

Tests conducted by Hobbs, et al. (2012) in support of proposed changes to the Actinide Removal Process facility operations evaluated potentially decreasing the MST concentration from 0.4 g/L to 0.2 g/L and the contact time from 12 hours to between 6 and 8 hours. In general, reducing the MST concentration from 0.4 to 0.2 g/L and increasing the ionic strength from 4.5 to 7.5 M in sodium concentration will decrease the measured decontamination factors for plutonium, neptunium, uranium and strontium. Sr DF above 100 are achievable. Initially plan on 0.4 g/l MST but this study shows some advantages of lower MST but could impact DF. Contact time 10 – 12 hours. They found that decreasing the MST concentration in the ARP from 0.4 g/L to 0.2 g/L will produce an increase in the filter flux, and could lead to longer operating times between filter cleaning. It was estimated that the reduction in MST could result in a reduction of filtration time of up to 20%.

While the approach proposed in this analysis will use 0.4 g/l MST, the work at SRS showed some advantages of lower MST but could impact DF. The proposed contact time is 10 – 12 hours.

A Technology Readiness Assessment Report was prepared in 2009 to examine the Salt Waste Processing Facility at the Savannah River Site (DOE, 2009). This assessment included the Alpha Strike Process where the SWPF feed is chemically adjusted and MST added as well as the subsequent cross-flow filtration unit. The MST adsorbs the Sr and actinides, and the resulting MST slurry is filtered to produce a concentrated MST/sludge slurry and a Clarified Salt Solution (CSS) filtrate. The concentrated MST/sludge slurry is washed to reduce the sodium ion (Na^+) concentration and transferred to the DWPF for vitrification while the CSS is routed to the CSSX process (DOE, 2009). The Feed Adjustment System was determined to be TRL 6 because of the range of laboratory- and bench-scale tests with actual waste and particularly by the large-scale equipment tests that involved batches of SWPF feed simulant. The cross flow filter system was also evaluated and determined to be at TRL 6. Laboratory scale tests with real wastes and full scale tests with a range of simulants using prototypical equipment have been completed.

Complexed Sr removal: Warrant, et al. (2013) have examined a method to simultaneously remove chelated ^{90}Sr and ^{241}Am from the liquid phase of high-level nuclear waste using sodium permanganate and cold strontium nitrate. This work extended previous work for treating diluted waste in the Hanford Waste Treatment and Immobilization facility (WTP). Both diluted and more concentrated waste from Hanford tank AN-107 was treated with 3.0 M $Sr(NO_3)_2$ and 3.8 M $NaMnO_4$. The removal of ^{90}Sr was essentially identical at both levels of dilution while the removal of ^{241}Am was slightly better in the diluted sample.

Sylvester and Clearfield (1999), evaluated two inorganic ion-exchange materials, a sodium nonatitanate and a sodium titanosilicate, for the removal of strontium from two simulated Hanford tank wastes (101-SY and 107-AN), both of which contained substantial amounts of complexing agents. They found that for simulant 101-SY, both exchangers gave distribution coefficients (*K*ds) of 220 mL/g at a volume-to-mass ratio of 200. However, for the 107-AN simulant, the titanosilicate gave a *K*d of 2240 mL/g while the nonatitanate gave a similar *K*d to the value obtained in the 101-SY simulant. This difference was attributed to the concentration of calcium in the waste simulants. High calcium concentration (as found in 107-AN) resulted in strontium, previously chelated by EDTA and other complexants, being released into solution and absorbed by the titanosilicate (Sylvester and Clearfield, 1999). Based on these finding they suggested the addition of calcium to the tank wastes to facilitate the removal of strontium by ion exchange as an economical approach to the remediation of complexant-bearing Hanford tank wastes

A.4 APPROACH TO PRETREATMENT

The conceptual flow sheet for the two grout cases is shown in Figure A.1. This is a relatively simple system for the chemical oxidation of the LDR organic, if required. The feed enters one of two feed tanks that are used for chemical analysis to determine the extent of pretreatment required. If it is determined that LRD organic removal is required, this will also be accomplished in this tank with the addition of a sodium permanganate strike and / or the use of ozone. The permanganate strike would also be expected to precipitate and remove much of the soluble TRU components from the waste feed. The contents of the vessel is then analyzed again to verity the effectiveness of the oxidation step prior to its transfer to the SLAW immobilization step.

In addition to the base grout cases evaluated, analysis of the risks and opportunities indicated that in some cases the level of Tc, and iodine could result in the grouted wasteform not meeting onsite disposal requirements. In these cases, Tc and/or Iodine removal as a pretreatment step would be considered as a risk mitigation. Additional LDR metal pretreatment is also considered as a potential mitigation process if the resulting wasteform fails the TCLP tests. The removal of Sr is considered a potential opportunity to change the waste classification of much of the resulting waste from Class B to Class A with a subsequent reduction in the disposal costs. The conceptual flow sheet for pretreatment if Tc, I, LDR metal and Sr removal are implement as either mitigation or as an opportunity to alter the waste classification is shown in Figure A.2. It consists of 4 primary treatment blocks, some or all of which can be bypassed based on pretreatment needs for specific batches of feed.

The feed enters one of two feed tanks that are used for chemical analysis to determine the pretreatment requirements. In this initial block of the flowsheet, should Sr removal be required it is conducted in this vessel with a preliminary MST strike. If additional removal is required (due to the presence of complexed Sr in the supernate), this is accomplished with the addition of the strontium nitrate feed. If LRD organic removal is required, this will also be accomplished in this tank with the addition of a sodium permanganate strike. The permanganate strike would also be expected to precipitate and remove much of the soluble TRU components from the waste feed. The contents of the vessel is then filtered using a cross-flow filter and the filtrate is transferred to the next required process. The slurry containing the Sr is sent to HLW Vit.

LDR metal removal is conducted in the second block, where if specific metals must be removed (instead of complexed in the final wasteform), this is carried out by the addition of appropriate reductants (TBD) and/ or complexing agents (TBD) for subsequent filtration. The filtered supernate is then transferred to the Tc and I removal feed tank. The solids slurry is sent to HLW Vit.

The third block is Tc removal by ion exchange using SuperLig 639^{TM}. The loaded columns are eluted with water and the Tc rich eluent is either sent to HLW Vit or solidified for shipment to WCS.

Iodine removal, if required is conducted using a silver based solid sorbent. The iodine-loaded sorbent from the iodine columns are either sent to HLW Vit or grouted for disposal at WCS.

A.5 Additional Areas for Evaluation

- Evaluate potential for exemptions from LDR requirements (e.g. No Migration Variance).
- Improve analytical methods to quantify levels of LDR organics in the feed vector.
- Demonstrate the oxidization of the full range of anticipated LDR organics either with permanganate alone or in combination with ozone.
    - Demonstrate a large scale ozonation system.
    - Determine mixing parameters, residence time, oxidation rates, etc.
    - Determine if the chemical oxidation results in the formation of other LDR organics.
    - Mature pretreatment technologies to TRL 8
- Evaluate feasibility of feed selection options (to redirect some high LDR organic SLAW to WTP) to minimize pretreatment scope for the grouting technology.
- Develop and demonstrate effective iodine removal from the caustic SLAW waste streams
    - Develop an iodine wasteform compatible with the removal method.
- Confirm that grout formulations will pass TCLP.
- Confirm the extent of Sr removal using CST.

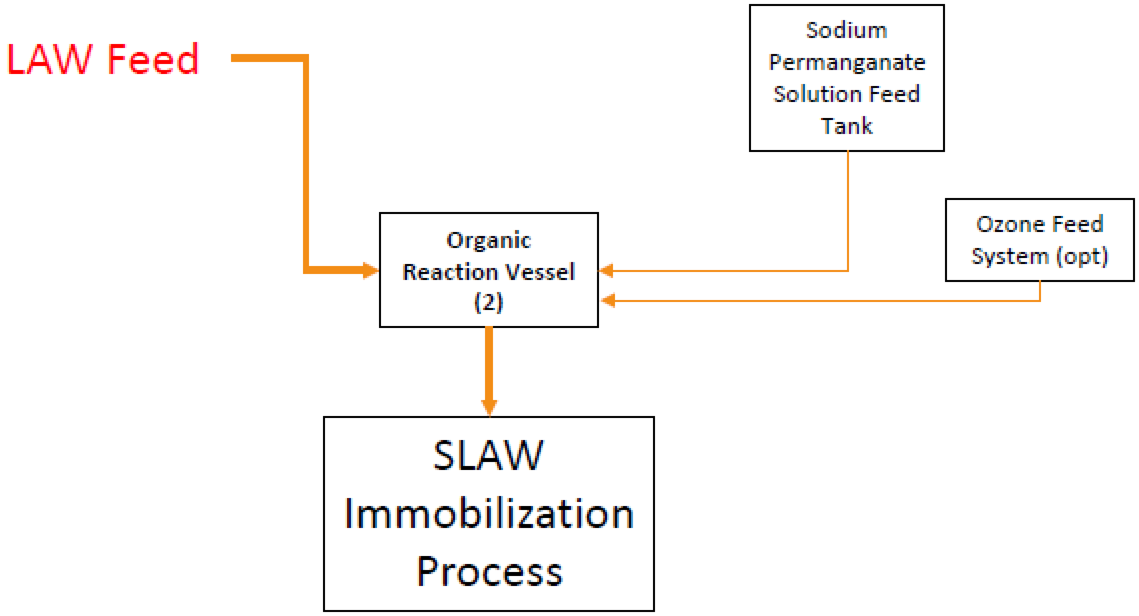

Figure A.1. SLAW Pretreatment Concept with LDR organic treatment only

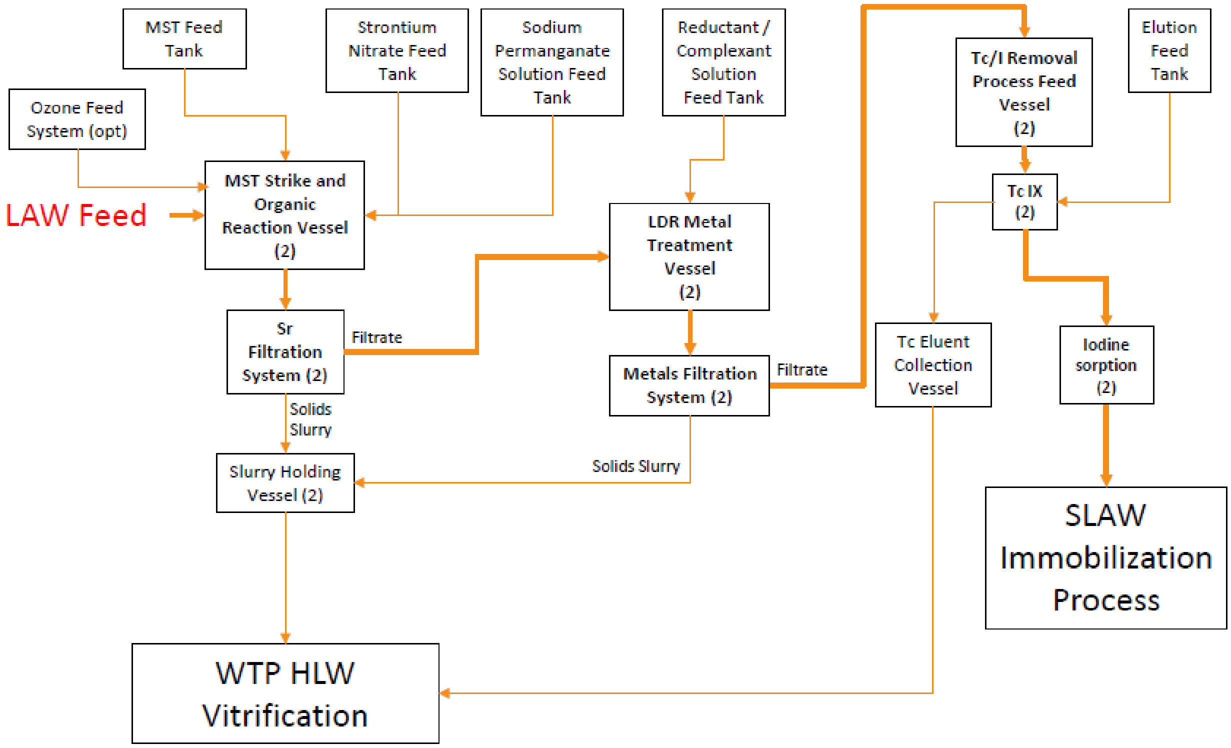

Figure A.2. SLAW Pretreatment Concept with Tc, I, LDR metal, and Sr removal

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APPENDIX B. VITRIFICATION

B.1 TECHNOLOGY OVERVIEW

Vitrification, per this document, implies high temperature conversion of treated feed slurry into a single phase melt, pouring the melt into a metal container, and allowing the melt to convert to an amorphous (non-crystalline) body. WTP process designs are consistent with other U.S. and most international waste vitrification efforts, wherein the waste feed is converted to a molten state within a joule-heated, ceramic lined melter. The use of electric melting – alternating current is passed through the molten mass creating heat by the joule effect – allows for submerged electrodes to maximize temperature within the molten mass and for the formation of a cold cap of melter feed. The cold cap is a mixture of anhydrous salts, hydroxides, oxides, etc. that fuse and incorporate into the melt. The cold cap acts a barrier to release of semi-volatile species (such as technetium), ultimately maximizing radionuclide retention.

Also similar to most nuclear waste vitrification processes and the WTP LAW facility, SLAW will use low-temperature alkali borosilicate glass compositions. Borosilicate glasses contain at least 5% boron oxide and exhibit favorable properties for waste stabilization: acceptable durability and resistance to water leaching for final wasteform, as well as processing characteristics achievable in the melter: low melting points, high electrical conductivity, low corrosion rates, and controllable viscosity.

Borosilicate glass incorporate the waste components into the amorphous glass matrix, forming bonds with the waste to become part of the glass. In a melt, silicon dioxide forms a matrix of tetrahedra. The melt is amorphous because the Si-O-Si bond angles are not the same, but distributed around ≈144°. When alkali waste components known as fluxes (such as sodium and potassium) are added to the glass, some of the Si-O bonds are broken and two alkali ions are loosely held in proximity to the non-bridging Si-O. The presence of the alkali (from the waste) lowers the melting temperature, viscosity, and durability, while raising the electrical conductivity. Other waste components and components added as glass forming chemicals such as alkaline earths and transition metals, are called property modifiers and offset the reduction in melting temperature and durability by altering the bonding structure of the glass. In this way, the waste is chemically bonded within the glass, becoming part of the structure, rather than being associated with or encapsulated by the glass.

The SLAW compositions are designed to be compatible with the melter material requirements (refractory, electrode, and bubbler materials of construction) with appropriate melt properties (viscosity and liquidus) at the 1150 ^{o}C operating temperature. Melt conductivity is a critical feature, as the melt acts as part of the electrical circuit. Conductivity is a strong function of alkali content; a minimum amount of alkali is necessary to carry sufficient current for processing requirements. At the same time, increasing alkali strongly deceases melt viscosity (low viscosity glasses are more corrosive) and final glass durability. Formulation design, therefore, is a careful balance of waste content (soda is the predominant oxide in the SLAW feed) and glass forming additives to achieve processing conditions, waste throughput, and wasteform properties.

The glass properties can also be influenced by species that are not incorporated into the glass matrix, such as nitrate, nitrite and other anions. Nitrate and nitrite will oxidize various metals (such as iron and manganese) during the cold cap reactions. Iron will remain in a high oxidization state (Fe+3) in the glass, but other metals (such as manganese and cerium) will revert back to a lower oxidization state at high temperatures, releasing oxygen into the melt pool. The released oxygen can result in a layer of foam between the melt pool and the cold cap, slowing melt reactions and limiting the feed rate. Sugar is added to the melter feed as a reducing agent that reacts with the oxidizing species in the cold cap and prevents oxygen release from the melt pool. If excess sugar is added, the glass pool can become too reducing and certain species (such as nickel and iron) will precipitate insoluble crystals that can separate from the molten glass and form a layer that can short-circuit the electrical path through the glass.

The selection of vitrification technology and glass formulation is effectively a single selection, albeit the glass formulation can be varied significantly. The glass composition must not only be compatible with melter materials for corrosion and duty temperature, but have compatible conductivity, viscosity, durability parameters to allow for effective production and product quality goals. The WTP Joule heated melters are designed to be efficient waste processing units, with specific feature to optimize production. For example, the WTP LAW melters feature 18 bubbler mechanisms – submerged air injection units that significantly improve melt convection and cold cap incorporation into the melt. This leads to a significantly higher melt throughput rate per melt surface area than achieved by current U.S. defense waste vitrification processing (DWPF).

Supplemental Low Activity Waste (SLAW) could be treated via vitrification, using an additional vitrification facility similar to the Waste Treatment and Immobilization Plant (WTP) LAW facility. This SLAW facility would receive treated supernate from the WTP Pretreatment facility (PT) and the LAW Pretreatment System (LAWPS).[48] Incoming feed is sampled and a series of glass property models are used to determine the required amount of glass forming chemicals (GFCs), sugar (reductant), and rheological control water to add to the waste. Joule-heated ceramic-lined melters will convert the slurry of waste and GFCs into a vitrified wasteform.[49] The GFCs are weighed and blended in a cold feed area per the recipe calculated using the glass property models. The blended GFCs are then transferred to the SLAW facility, weighed, and mixed with the waste to form melter feed slurry. The slurry is fed to the melter where the feed is heated. The resulting glass is poured into containers where it solidifies into an immobilized LAW glass. Water, volatile components, and portions of the semi-volatile components are partitioned to the melter offgas system. The LAW glass containers are staged and then transferred to the Integrated Disposal Facility (IDF). The vitrified wasteform is expected to meet the IDF Waste Acceptance Criteria (WAC) and be a modest contributor to the release of contaminants of concern to the environment when modeled in the IDF Performance Assessment (IDF-PA).

The melter offgas treatment system will condense the water and volatile components as well as remove entrained particulate from the offgas.[50] The resulting condensate is collected and transferred to an Effluent Management Facility (EMF). Additional treatment of the offgas is performed to remove mercury, iodine, acid gases, any remaining particulate, and any residual organics.

The EMF will receive liquid effluents from the SLAW melters.[51] These liquid secondary waste effluents will be evaporated and the overheads are transferred to the Liquid Effluent Receipt Facility/Effluent Treatment Facility (LERF/ETF) for further treatment and ultimate disposal as a grouted wasteform in the IDF. The concentrate will be recycled to the front end of the SLAW process.

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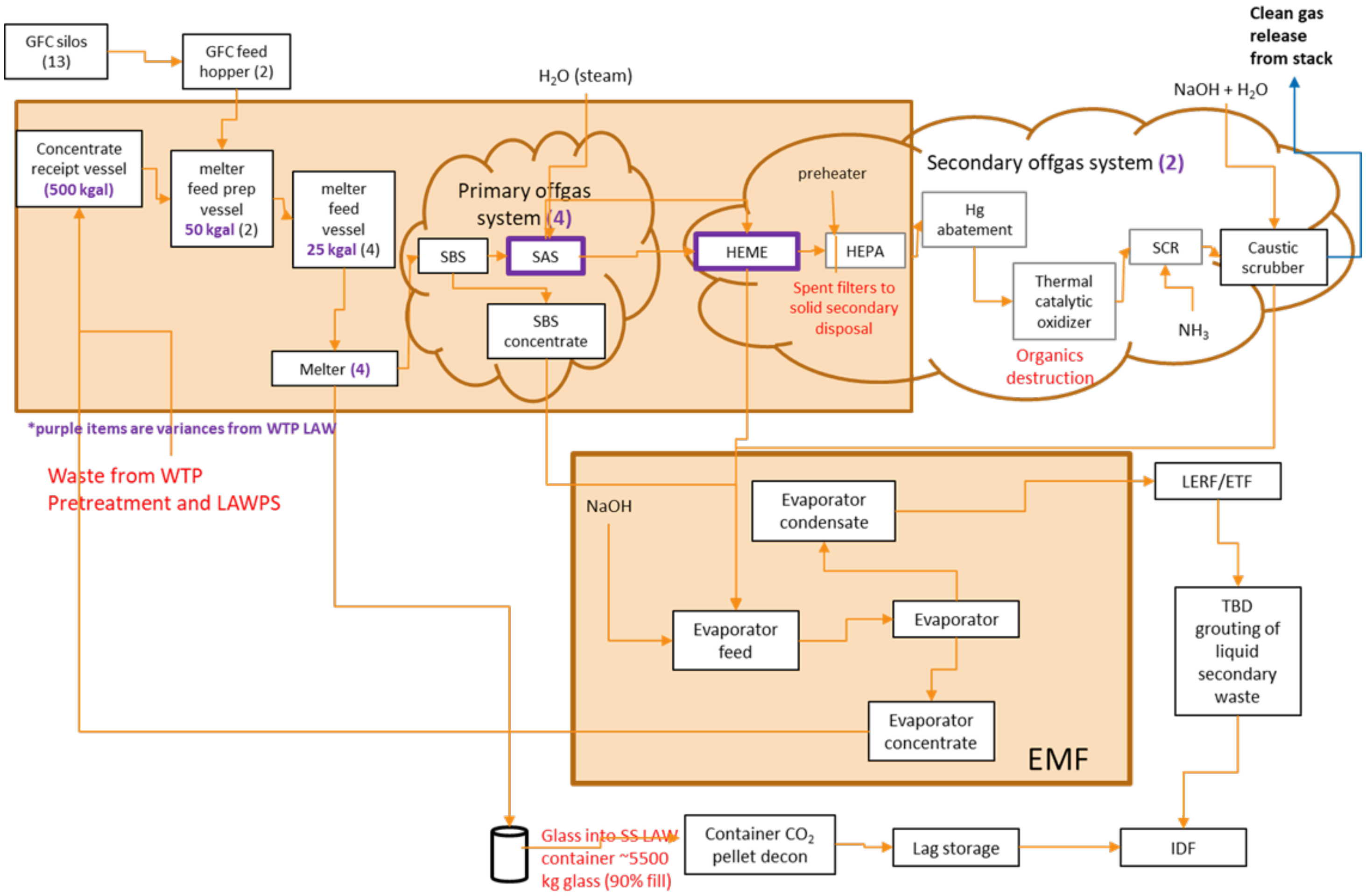
B.2 DESCRIPTIONS OF FLOWSHEETS

The baseline vitrification flowsheet mimics the Immobilized Low Activity Waste (ILAW) vitrification flowsheet with changes incorporated into vessel sizing (to provide relief to sample analysis turnaround time) and select offgas components. Alternative flowsheets were also considered in this assessment. The baseline and alternative flowsheets are described in the sections that follow.

B.2.1 Baseline

The baseline flowsheet for this evaluation consists of 1) melter feed systems that include receipt and handing of treated waste from PT and LAWPS, receipt of concentrated effluent from EMF, as well as GFC handling and blending; 2) four melters; 3) four offgas trains (each with primary and secondary systems); 4) an EMF (the EMF currently under construction is sized to support LAWPS only, not SLAW); 5) and a glass container handling, decontamination, and temporary lag storage facility. Each of these unit operations is outlined in the figure below and described in the following subsections.



EMF	Effluent Management Facility
GFC	Glass forming chemical
HEME	High efficiency mist eliminator
IDF	Integrated Disposal Facility
LERF/ETF	Liquid Effluent Receipt Facility/Effluent Treatment Facility
SAS	Steam atomized scrubber
SBS	Submerged bed scrubber
SCR	Selective catalytic reduction
SS	Stainless steel

B.2.1.1 Melter Feed System

Treated waste from PT and LAWPS will be received into a 500 kgal concentrate receipt vessel (CRV) and blended with the recycle stream from EMF. The volume of this vessel was selected as being sufficient to maintain feed for four melter lines. The vessel will have ongoing in/out transfers and provide lag storage capability. Blended waste from the CRV will be transferred into two 50 kgal, actively cooled, melter feed preparation vessels (MFPV). Each MFPV will be sampled and analyzed to provide input to the glass property models[52,53] to determine the GFC and sucrose additions required for formulation of a compliant glass.[54] This differs somewhat from the WTP LAW facility, where sampling for compliance will occur in the CRV, though the MFPV will still be sampled.[55] This sample is considered a process hold point to demonstrate waste compliance.[56] Based on the output of the glass property models, GFCs will be weighed from each of 13 GFC silos, batched, blended, and transferred to the GFC hopper. The glass former storage and preparation system is assumed to be of the same design and capability as those of the WTP Balance of Facilities (BOF) glass former handling facility,[57] but with its scale doubled to support the operation of four melters. The GFCs, their mineral sources,[58] and acceptable levels of impurities[59] are assumed to be the same as those specified for the WTP LAW operation. Note that a risk exists regarding future availability of the selected mineral sources of the GFCs. The blended GFCs will be wetted to prevent dusting[60] and fed to the MFPV. Dilution water mass is added to the feed if needed to meet melter feed rheological requirements,[61] with dilution water added as needed. After the GFCs and treated waste are blended in the MFPV, the slurry is transferred to one of the four 25 kgal, actively cooled, melter feed vessels (MFV). One MFV will feed each melter. Each MFV will have capabilities for mechanical agitation to maintain suspension of the GFC solids, pumps for transfer of blended feed to the melter, and pumps for return of the feed to the MFV in case of a melter shutdown.

All unit operations of the melter feed system must be operational to maintain continuous feed to the melters as required to produce 15 metric tons of glass (MTG) per day per melter. The design of each unit operation is generally assumed to be equivalent to the corresponding unit operations of the WTP LAW melter feed process.[62]

B.2.1.2 Melters

Melter feed slurry from the MFVs will be fed to each of the four identical melters. The melters are joule-heated, refractory ceramic-lined vessels heated to ~1150 °C to vitrify the waste, and are assumed to be of the same design as the WTP LAW melters.[63] The outer surfaces of the melter and pour chambers are actively cooled. Glass temperatures are measured via submerged thermocouples and controlled by adjusting the electrode power.

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[52] 24590-LAW-RPT-RT-04-0003, Rev 1, Preliminary ILAW Formulation Algorithm Description

[53] 24590-101-TSA-W000-0009-72-00012, Letter Report – Proposed Approach for Development of LAW Glass Formulation Correlation

[54] 24590-WTP-PL-RT-03-001, ILAW Product Compliance Plan

[55] "Flowsheet Bases, Assumptions, and Requirements," 24590-WTP-RPT-PT-02-005, Revision 8, Bechtel National Incorporated, River Protection Project, Waste Treatment Plant, Richland, Washington, 2016.

[56] "Flowsheet Bases, Assumptions, and Requirements," 24590-WTP-RPT-PT-02-005, Revision 8, Bechtel National Incorporated, River Protection Project, Waste Treatment Plant, Richland, Washington, 2016.

[57] 24590-LAW-3ZD-LFP-00001, LAW Melter Feed Process (LFP) and Concentrate Receipt Process (LCP) System Design Description

[58] R.F. Schumacher, "Characterization of HLW and Law Glass Formers," Westinghouse Savannah River Company, Aiken, SC, WSRC-TR-2002-00282, Rev. 1, 2003.

[59] SCT-M0SRLE60-00-175-01, Final Report - Characterization of HLW and LAW Glass Formers

[60] CCN 077705, Evaluation of Wetting Agents for Glass Former Dusting Control (RTC 170)

[61] 24590-WTP-RPT-PO-03-007, LAW Melter Feed Rheology Assessment

[62] 24590-WTP-RPT-PT-02-005, Rev 8, Flowsheet Bases, Assumptions, and Requirements

[63] 24590-101-TSA-W000-0010-409-359, LAW Melter System Description

Each melter can produce 15 metric tons of glass per day.[55] The glass must meet melter compatibility requirements including viscosity, electrical conductivity, and liquidus temperature.[64] These properties are controlled via glass formulation as dictated by the glass property models.[52,53] In addition to meeting the processing requirements described above, the glass property models are tasked to produce a glass wasteform that is compliant with the specifications for disposal, i.e., Product Consistency Test (PCT) ASTM C1285, the Vapor Hydration Test (VHT) ASTM C1663, and the Toxic Characteristic Leaching Procedure (TCLP EPA Manual SW-846 Procedure 1311) as described in the ILAW Product Compliance Plan.

At steady-state, the melter operation (feed rate, melter power, bubbling rate, etc.) is controlled to maintain a cold cap of partially reacted feed on top of the pool of molten glass. Additional feed enters from side nozzles at the top of the melter. The cold cap assists with retention of volatile and semi-volatile components in the ILAW glass product. A range of chemical reactions occur as the feed is converted to glass in the cold cap. Sugar that is added with the GFCs controls the REDOX reactions in the cold cap. The water from the feed slurry also is evaporated into the offgas system. Multiple compressed air bubblers are operated in the melter to agitate the molten glass pool, improve temperature uniformity, and transfer additional heat to the cold cap.

The operation of the melter to maintain the cold cap represents a fine balance between under-feeding the melter, which would allow the cold cap to burn off—releasing volatile species into the offgas system--and over-feeding the melter which would allow excessive amounts of material to accumulate in the cold cap. This balance will be maintained in the LAW melter systems primarily through control of the feed rate and bubbling rate. The need to maintain a cold cap to aid in retention of semi-volatile species limits the turn-down ability of the melters as feed rates must be kept high enough to form a cold cap. It should be noted that entrainment of feed into the offgas is impacted by the feed and bubbling rates, with higher entrainment expected as feed or bubbling rate are increased.

When the feed to the melter is stopped, the cold cap is burned off and any semi-volatile species in the melt pool will gradually vaporize into the offgas stream as turning the melter off (or significantly reducing the temperature in the melter) could allow crystalline formations to form that would require replacement of the melter.

The resulting glass exits the melter via one of two identical discharge chambers. An air lift in a riser displaces the glass up into a trough where it will gravity drain into a stainless steel LAW container. Electrical resistance heaters maintain sufficient temperature for the glass to flow within the discharge chambers. The glass pouring rate is higher than the rate of feed conversion to glass; thus, pouring occurs in incremental steps, alternating between the two chambers. The higher pouring rate also facilitates flow of glass to the periphery of the containers as they are filled. The glass level in the melter is monitored using pneumatic probes, and the level dictates the starting and stopping points of the pouring cycles. Approximately five pouring cycles are needed to fill each container.

The design life of a melter is five years.[55] Bubbler replacement is expected to be the most frequent maintenance requirement,[55] with each bubbler having an estimated life span of 26 weeks.[65,66] Each melter has three racks of six bubblers. A rack in each melter is replaced every eight weeks. The melter is not fed during bubbler replacement.

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[64] 24590-LAW-3PS-AE00-T0001, Engineering Specification for Low Activity Waste Melters

[65] 24590-101-TSA-W000-0010-08-10, Rev 00C, Report – RPP Pilot Melter Bubbler Life Extension Test Results Report

[66] CCN 103214, Update to the LAW Reliability, Availability, and Maintainability (RAM) Data for the LCP, LFP, LMP, GFR, LOP, and LVP Systems

B.2.1.3 Offgas Trains

The offgas systems treat the gases from the melters and vessels such that they meet air discharge permitting requirements. The offgas system design assumed for this evaluation is mostly similar to that for WTP LAW.[55] The difference is the use of a steam atomized scrubber (SAS) and high efficiency mist eliminator (HEME) in place of a wet electrostatic precipitator (WESP). Assumptions regarding the types and quantities of offgas species, decontamination factors, particulate concentrations, and gas generation rates are equivalent to those for the WTP LAW facility.[55]

The offgas generated from each of the melters exits via a film cooler and enters the primary offgas train. The temperature of the offgas is reduced in the film cooler to reduce the amount of material adhering to the offgas piping. A backup film cooler is available should the primary system fail. The cooled offgas will then be condensed in a submerged bed scrubber (SBS). The SBS also removes entrained particulates from the gas stream. As the offgas is condensed, the overflow from the SBS will be collected in a condensate vessel and transferred to the EMF evaporator feed tank. The offgas next passes through a SAS to remove additional particulates. Condensed liquids from the SAS will be recycled to supply the HEME that will remove soluble components and protect the downstream high efficiency particulate air (HEPA) filter from moisture. The offgas will then enter the secondary offgas train. Vessel ventilation from the melter feed system joins the secondary offgas train at this point. The secondary offgas train is assumed to be identical to that designed for WTP LAW, and is described in further detail elsewhere.[67] In short, HEPA filters will remove any remaining particulate material from the offgas. A preheater prior to the filters reduces the relative humidity of the gas to prevent condensation in the filters. Spent HEPA filters will be transferred to the Central Waste Complex for grouting as Secondary Solid Waste prior to disposal at the IDF.[68] The resulting offgas will exit the radioactive containment area and will be treated to remove mercury, acid gas, and halides using granular activated carbon (GAC) adsorbers. The GAC filters also will be transferred to the Central Waste Complex for grouting as Secondary Solid Waste prior to disposal at the IDF. The gas stream is then reheated so that any remaining organics can be destroyed using thermal catalytic oxidation. The NO_x will be reduced to nitrogen with ammonia using selective catalytic reduction, and finally, any remaining acid gases will be neutralized in a caustic scrubber. The caustic scrubber solution will be transferred to the LERF/ETF with the condensate from the EMF for further treatment. Offgas exiting the caustic scrubber is drawn through a set of exhausters, which maintain the motive force for offgas movement, and is released to the stack.

B.2.1.4 Effluent Management Facility

The WTP Effluent Management Facility (EMF) to support DFLAW is currently in design. The EMF to support SLAW is expected to handle twice the capacity of the WTP EMF. The SLAW EMF will receive effluents from the four offgas trains associated with the four melters, from line flushing and draining, and from various equipment decontamination operations within the SLAW facility. The effluents will be concentrated in the EMF evaporator. Anti-foam and caustic additions are available to control process chemistry. Concentrate will be recycled back into the CRV for immobilization and condensate will be transferred to the LERF/ETF for additional treatment. Corrosion control limits of the materials of construction will be determined by the concentration of halides in the carryover from the melt offgas. It is assumed that LERF/ETF has sufficient capability to process condensate from the SLAW EMF based on the design capacity and assumptions in the Integrated Flowsheet for LERF/ETF capacity. It is noted that LERF/ETF has not demonstrated continuous operation at rates sufficient for treating the effluent from SLAW, but upgrades are assumed in SP8.

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[67] 24590-LAW-3YD-LOP-00001, Rev 3

[68] "River Protection Project System Plan," ORP-11242, Revision 8, DOE Office of River Protection, Richland, Washington, 2017.

For each gallon of waste in the CRV, the process produces ~ 0.5 gallons of glass. The current ILAW flowsheet is calculated to produce ~1.5 gallons of offgas effluent for each gallon of waste in the CRV, not including flushes in the WTP system.[55] For comparison, the SRS Defense Waste Processing Facility (DWPF) returns 5 gallons of liquid to the tank farm for each gallon of sludge vitrified.[69] Therefore, there is a risk that the current ILAW flowsheet underestimates the volume of liquid secondary waste that will be produced. Both DOE and the contractor are aware of this risk, and further discussion is outside the scope of this task.

B.2.1.5 Glass Containers

The glass disposal containers are stainless steel, 4 ft in diameter and 7.5 ft tall (24590-LAW-M0-LRH-00004002, LAW Vitrification System LRH Product Container Weldment Details) right circular cylinders holding 564 gallons of glass.[55] Systems for the mechanical handling of canisters, from receipt of empty canisters into the facility to export of finished canisters for burial, are assumed to be the same as those designed for WTP LAW.[70,71,72,73]

The vitrified waste is poured into the containers, which hold ~6 metric tons (~2,000 gallons feed from the CRV) of vitrified waste.[55] The containers are cooled, inspected for fill height (if fill height is not ≥ 90%, inert fill is added), and sealed. The sealed containers are decontaminated by CO_2 pellet blasting to meet requirements for minimal removable contamination. This system is assumed to be of the same design as that for WTP LAW.[55,74] The gas and particulate stream is drawn through HEPA filters, and then exhausts to the building ventilation system. Spent HEPA filters will be transferred to the Central Waste Complex for encapsulation as Secondary Solid Waste prior to disposal at the IDF.[75] Finished containers are stored until transfer to the IDF.

B.2.2 Alternative Flowsheets

B.2.2.1 Vitrification with Offsite Disposal of Secondary Waste

This alternative flowsheet is similar to SLAW immobilization via vitrification, with the difference being that the EMF evaporator concentrate will be immobilized in a grout wasteform and shipped offsite for disposal, rather than being recycled back to the CRV at the front end of the vitrification process. Breaking the recycle loop would address the challenge of capturing volatile and semi-volatile contaminants of concern in the glass wasteform, reduce the burden on the liquid secondary waste processing facilities, and reduce the source term for ILAW in the Hanford IDF.

Implementation of the alternative flowsheet will require the design and construction of a facility for immobilizing liquid secondary waste in grout. DOE experience with similar facilities would be leveraged for this purpose. A grout wasteform production facility is relatively simple, with four main unit operations: raw materials receipt, storage, and blending; mixing of raw materials with the liquid waste stream; pouring of the grout slurry into containers; and curing and shipping of the filled containers. It is assumed that secondary waste immobilized in grout would be acceptable at an offsite disposal facility, such as the Waste Control Specialists facility in west Texas. It is also assumed that secondary waste immobilized in grout would meet shipping regulations for transportation to the disposal site.

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[69] "DWPF Recycle Evaporator Flowsheet Evaluation (U)," WSRC-TR-2005-00226, Revision 1, Savannah River National Laboratory, Aiken, South Carolina, 2005.

[70] 24590-LAW-3ZD-LRH-00001, Rev 0, LAW Container Receipt Handling (LRH) System Design Description

[71] 24590-LAW-3ZD-LPH-00001, Rev 0, LAW Container Pour Handling (LPH) System Design Description

[72] 24590-LAW-3ZD-LFH-00001, Rev 0, LAW Container Finishing Handling (LFH) System Design Description

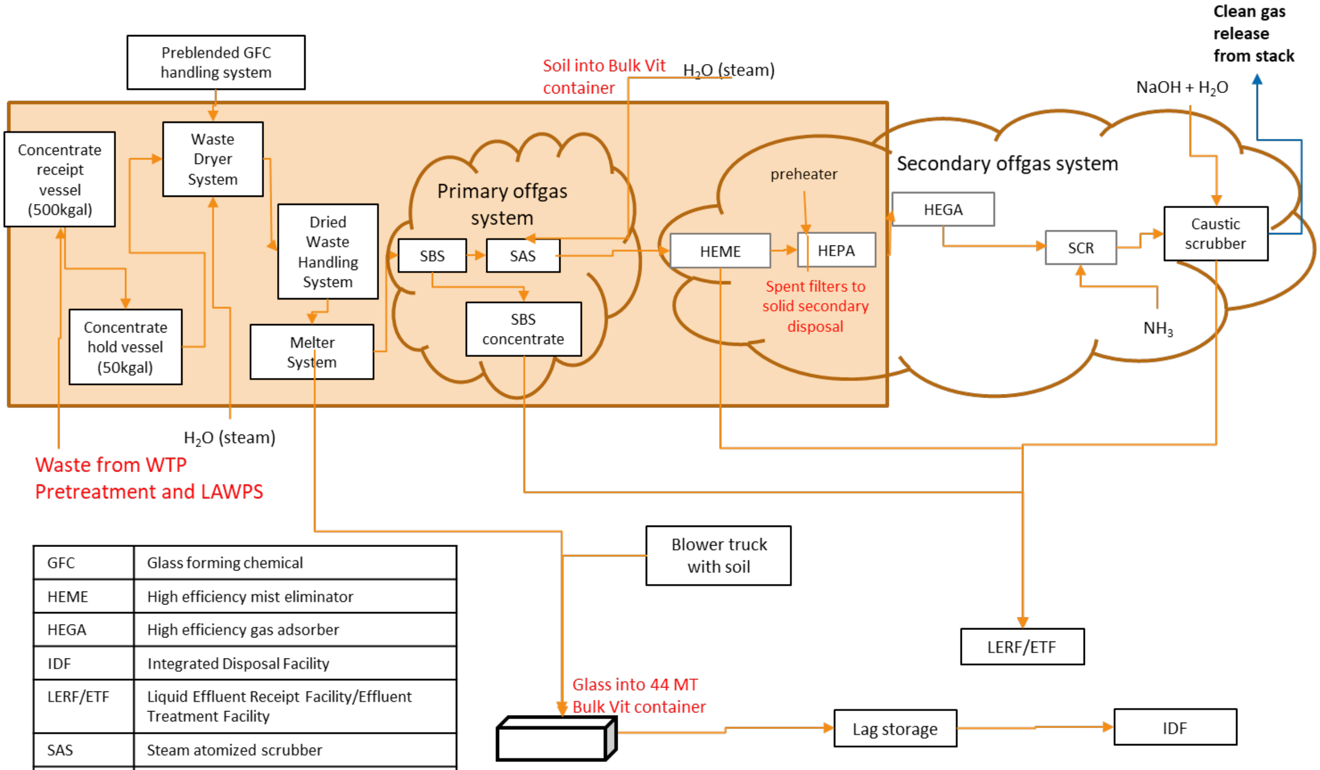
[73] 24590-LAW-3ZD-LEH-00001, Rev 0, LAW Container Export Handling (LEH) System Design Description

[74] 24590-LAW-M5-V17T-00013, Process Flow Diagram LAW Vitrification Container Decontamination (System CDG)

[75] "River Protection Project System Plan," ORP-11242, Revision 8, DOE Office of River Protection, Richland, Washington, 2017.

B.2.2.2 In Container Vitrification™

For In Container Vitrification (ICV), the SLAW facility will receive treated supernate from WTP PT and LAWPS.[48] Pre-blended GFCs and cellulose (reductant) are added to the waste. The waste and additives are blended and dried into melter feed. The dried feed is added to the melt container as melting occurs. Heating is provided via graphite electrodes that transfer the alternating electrical current through the dried waste.[76] Offgas from the melting process is captured by a hood sealed to the container and will be treated similarly to the offgas train in the vitrification flowsheet described earlier. Each of these unit operations is outlined in the figure below and described in the following subsections.



GFC	Glass forming chemical
HEME	High efficiency mist eliminator
HEGA	High efficiency gas adsorber
IDF	Integrated Disposal Facility
LERF/ETF	Liquid Effluent Receipt Facility/Effluent Treatment Facility
SAS	Steam atomized scrubber
SBS	Submerged bed scrubber
SCR	Selective catalytic reduction

B.2.2.3 Melter Feed System

Treated waste from PT and LAWPS will be received into a 500 kgal concentrate receipt vessel (CRV) and blended. The volume of this vessel was selected as being sufficient to maintain feed for two ICV stations. The vessel will have ongoing in/out transfers and provides lag storage capability. Blended waste from the CRV will be transferred into a 50 kgal, hold vessel. The waste in the concentrate hold vessel is analyzed to determine the GFC additions. This sample will serve as a process hold point to demonstrate waste compliance. Pre-blended GFCs and cellulose are conveyed to the waste dryer. The waste dryer is a steam jacketed, vacuum evaporator with rotating plows to agitate the waste/FC blend. The waste dryer initiates mixing and heating prior to adding waste. The waste volume added to the dryer is added incrementally. The waste addition rate is maintained below the evaporation rate to maintain a dry bed in the dryer. Offgas from the dryer is condensed and collected. The uncondensed portion of the offgas is routed through the offgas system. After the waste and GFCs have been blended and dried, ~20% is discharged to the dried waste handling system and additional GFCs are added to the dryer followed by waste additions. The dried melter feed is gravity fed to the melt container.

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[76] "Bulk Vitrification Technology for the Treatment and Immobilization of Low-Activity Waste," RPP-48703, Revision 0, Washington River Protection Solutions, Richland, Washington, 2011.

B.2.2.4 Melters

Dried melter feed is gravity fed to the pre-staged melt container. The melt container is a 7.S-ft (tall) x 7.S-ft (wide) x 24-ft (long) roll off box. Prior to being positioned under the melter feed system, the box has a cast refractory lining and a sand barrier between the refractory and the container. The bottom of the container is pre-loaded with a 50/50 coal/glass mixture to facilitate melt initiation.

B.2.2.5 Offgas Trains

The offgas systems treat the gases from the melters and vessels such that they meet air discharge permitting requirements. The offgas system design assumed for this evaluation is mostly similar to that for WTP LAW.[55] The difference is the use of a steam atomized scrubber (SAS) and high efficiency mist eliminator (HEME) in place of a wet electrostatic precipitator (WESP). Assumptions regarding the types and quantities of offgas species, decontamination factors, particulate concentrations, and gas generation rates are the same as those for the WTP LAW facility.[55]

The offgas generated from each of the melters exits via a film cooler and enters the primary offgas train. The temperature of the offgas is reduced in the film cooler to reduce the amount of material adhering to the offgas piping. A backup film cooler is available should the primary system fail. The cooled offgas will then be condensed in a submerged bed scrubber (SBS). The SBS also removes entrained particulates from the gas stream. As the offgas is condensed, the overflow from the SBS will be collected in a condensate vessel and transferred to the EMF evaporator feed tank. The offgas next passes through a SAS to remove additional particulates. Condensed liquids from the SAS will be recycled to supply the HEME that will remove soluble components and protect the downstream high efficiency particulate air (HEPA) filter from moisture. The offgas will then enter the secondary offgas train. Vessel ventilation from the melter feed system joins the secondary offgas train at this point. The secondary offgas train is assumed to be identical to that designed for WTP LAW, and is described in further detail elsewhere.[77] In short, HEPA filters will remove any remaining particulate material from the offgas. A preheater prior to the filters reduces the relative humidity of the gas to prevent condensation in the filters. Spent HEPA filters will be transferred to the Central Waste Complex for grouting as Secondary Solid Waste prior to disposal at the IDF.[78] The resulting offgas will exit the radioactive containment area and will be treated to remove mercury, acid gas, and halides using granular activated carbon adsorbers. The gas stream is then reheated so that any remaining organics can be destroyed using thermal catalytic oxidation. The NO_x will be reduced to nitrogen with ammonia using selective catalytic reduction, and finally, any remaining acid gases will be neutralized in a caustic scrubber. The caustic scrubber solution will be transferred to the LERF/ETF with the condensate from the EMF for further treatment. Offgas exiting the caustic scrubber is drawn through a set of exhausters, which maintain the motive force for offgas movement, and is released to the stack.

B.2.2.6 Effluent Management Facility

The WTP Effluent Management Facility (EMF) to support DFLAW is currently in design. The EMF to support SLAW is expected to handle twice the capacity of the WTP EMF. The SLAW EMF will receive effluents from the two offgas trains associated with the two melter systems, and from various equipment decontamination operations within the SLAW facility. The effluents will be concentrated in the EMF evaporator. Anti-foam and caustic additions are available to control process chemistry. Concentrate will be recycled back into the CRV for immobilization and condensate will be transferred to the LERF/ETF for additional treatment. Corrosion control limits of the materials of construction will be determined by the concentration of halides in the carryover from the melter offgas. It is assumed that LERF/ETF has sufficient capability to treat condensate from the SLAW EMF

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[77] 24590-LAW-3YD-LOP-00001, Rev 3

[78] "River Protection Project System Plan," ORP-11242, Revision 8, DOE Office of River Protection, Richland, Washington, 2017.

based on the design capacity and assumptions in the Integrated Flowsheet for LERF/ETF capacity. It is noted that LERF/ETF has not demonstrated continuous operation at rates sufficient for treating the effluent from SLAW, but upgrades are assumed in SP8.

Similar to the melters, for each gallon of waste in the CRV, the process produces ~ 0.5 gallons of glass. The current ILAW flowsheet is calculated to produce ~1.5 gallons of offgas effluent for each gallon of waste in the CRV, not including flushes in the WTP system.[55] For comparison, the SRS Defense Waste Processing Facility (DWPF) returns 5 gallons of liquid to the tank farm for each gallon of sludge vitrified.[79] Therefore, there is a risk that the current ILAW flowsheet underestimates the volume of liquid secondary waste that will be produced. Both DOE and the contractor are aware of this risk and further discussion is outside the scope of this task.

B.2.2.7 Glass Containers

The melt containers described in B.2.2.2 also serve as the glass disposal containers. Systems for the mechanical handling of canisters, from receipt of empty canisters into the facility to export of finished canisters for burial, are assumed to be the same as those designed for WTP LAW.[80,81,82,83]

A completed ICV waste box contains approximately 44 metric tons of vitrified product. This is made up from 63 metric tons liquid waste from the CRV, 37 metric tons of glass formers and cellulose, and 2 metric tons of clean glass layer. The ICV box is topped off with 5 metric tons of soil.[84] Finished containers are stored until transfer to the IDF.

B.3 ASSUMPTIONS

The following assumptions are made regarding the baseline vitrification flowsheet:

- Tank waste retrieval and pretreatment via WTP PT and DFLAW have the sprint capacity to feed four SLAW vitrification lines
- The CRV volume of 500 kgal is sufficient to provide continuous feed to four SLAW vitrification lines
- The existing WTP Lab has sufficient capacity to support sampling and analysis of the four MFPVs
- The WTP LAW Control Room has sufficient reserve capacity to support four SLAW vitrification lines
- The Hanford IDF has sufficient capacity for disposal of the ILAW containers produced by SLAW vitrification
- The Hanford IDF has sufficient capacity for disposal of encapsulated HEPA filters from SLAW vitrification, including those from the offgas trains and from container decontamination
- Plant availability and maintenance times are equivalent to those assumed for WTP LAW vitrification
- Spent carbon beds, spent catalyst from the TCO, and spent catalyst from the SCR are disposed of in the Hanford IDF as solid secondary waste
- The EMF to support LAWPS is successfully designed, operated, and constructed, to serve as a basis for the larger EMF assumed for SLAW vitrification
- The Hanford LERF/ETF has sufficient capability to process condensate from the SLAW EMF.

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[79] "DWPF Recycle Evaporator Flowsheet Evaluation (U)," WSRC-TR-2005-00226, Revision 1, Savannah River National Laboratory, Aiken, South Carolina, 2005.

[80] 24590-LAW-3ZD-LRH-00001, Rev 0, LAW Container Receipt Handling (LRH) System Design Description

[81] 24590-LAW-3ZD-LPH-00001, Rev 0, LAW Container Pour Handling (LPH) System Design Description

[82] 24590-LAW-3ZD-LFH-00001, Rev 0, LAW Container Finishing Handling (LFH) System Design Description

[83] 24590-LAW-3ZD-LEH-00001, Rev 0, LAW Container Export Handling (LEH) System Design Description

[84] CH2M-36501-FP, Rev 0, Design of the Demonstration Bulk Vitrification System for the Supplemental Treatment of Low Activity Tank Waste at Hanford

The following assumptions are made regarding the alternative flowsheets for vitrification with offsite disposal of secondary waste:

- Appropriate raw materials are available in the Hanford area for producing a grout wasteform with the secondary waste
- Approvals can be obtained for transportation and offsite disposal of secondary waste immobilized in grout

B.4 RISKS/OBSTACLES TO IMPLEMENTATION

Risks associated with the baseline vitrification flowsheet include:

- Significant changes to the WTP LAW unit operations (from feed preparation through offgas treatment) during startup and initial hot operations would directly impact SLAW immobilization via vitrification
- The current assumptions for LAW WTP facility availability are higher than achievable in actual operation
- Availability of the specified GFCs may change before facility operation begins
- The radionuclide DFs of the full scale melter are lower than expected, increasing the burden on EMF and recycle
- The impact of melter idling on secondary waste volume generation is not considered in current integrated flow-sheet models. Increased carryover of volatile radionuclides into the offgas system will increase the amount of radionuclides present in the liquid and solid secondary waste streams.
- The current ILAW flowsheet underestimates the volume of liquid secondary waste that will be produced

Risks associated with the alternative flowsheets for vitrification with offsite disposal of secondary waste include:

- Appropriate raw materials are not available in the Hanford area for producing a grout wasteform
- Approval is not obtained for offsite transportation of secondary waste immobilized in grout
- An offsite disposal facility is no longer available

B.5 BENEFITS

Benefits of vitrification as an option to address SLAW include:

- Design of facility can be leveraged from existing ILAW design (most technically mature technology)
- Wasteform has been studied extensively, so minimal further research is required
- High temperature destroys LDR organics and most nitrates
- Low primary waste volume.

B.6 COSTS

Based on the current LAW facility, vitrification has the highest estimated costs among the options evaluated, ranging from ~$20 to $36B, as shown in Table 4.

Table B-1 Estimated costs for Vitrification

Vitrification	Low End	Analog Estimate	High End	Comments
Technology Development	340	-----------------------	760	Set at 5% of TPC
Pilot Operations	1080	1800	2520	See Note 2.
Total Project Cost (TPC)	6840	7600	15200	(-10% / +100%)
Operations (OPEX)	10080	12600	15120	(-20% / +20%)
Major Equipment	1400	-----------------------	2100	See Note 3.
Total Program Cost	19700		35700	

Vitrification costs note 1: Values are rounded.

Vitrification costs note 2: Pilot estimate driven by the integration of equipment, systems and type of testing. Pilot effort is assumed consistent for FBSR and Vitrification.
Vitrification costs note 3: Major equipment cost is driven by planned melter replacement and consumable melt bubblers. WTP-LAW melters have a nominal lifespan of 5 years. The 18 Inconel bubblers in each melter have a projected lifespan of 6 months. There will be nominally 24 melters required, each requiring 180 bubblers.

B.7 SCHEDULE

The estimated time to complete additional research & development, design, construction, and cold start (i.e., to hot startup) for the SLAW vitrification process is >10-15 years.

B.8 REGULATORY COMPLIANCE

Vitrified SLAW has been demonstrated for the PA and EIS to provide acceptable release of radionuclide and chemical species. Fifty containers of ICV SLAW have been permitted for disposal in the IDF as a demonstration.

Disposal of secondary waste at both IDF and WCS has been demonstrated to meet regulatory requirements, except that the levels of iodine-129 in the activated carbon require mitigation for IDF disposal. The disposal of secondary waste at the IDF is not included in the current permit. As noted above, Tc-99 and I-129 in secondary waste may be higher than assumed in the current IDF PA.

APPENDIX C. GROUTING

C.1 TECHNOLOGY OVERVIEW

C.1.1 Grout Overview

Grout technology involves mixing of an aqueous waste stream with various dry reagents to produce a slurry that is transferred into a waste container to solidify. The slurry reacts over a period of time to produce a solid, which encapsulates the constituents of concern in a solid waste-form. The initial solidification occurs over hours to days but reactions continue to evolve over years. The solidification reactions are exothermic.

The reagents used in cementation processes are inorganic materials that react with water to form solid, moisture-resistant wasteforms. Grout technology has a long history of being used to transform radioactive aqueous liquid and sludge waste streams into solid wasteforms for disposal at ambient temperature or near ambient temperature.

Two types of cement systems, hydraulic cements and acid-base cements, are used for radioactive waste solidification as well as for encapsulation of radioactive particulate waste and debris. The most common hydraulic cements used are based on ordinary Portland cement (OPC), which is a mixture of anhydrous calcium silicates, calcium aluminate, and calcium sulfate compounds. Often, grout technology utilizes dry mixes where the OPC is blended with other reactive ingredients selected to tailor characteristics of the final waste-form. Calcium aluminate cements, calcium sulfoaluminate cements, lime-pozzolan cements, calcium sulfate cements, and alkali activated slags and slag cements have also been successfully used. The most common acid-base cements used for radioactive waste conditioning are made by combining an acid (e.g., H_3PO_4 or KH_2PO_4, liquid or powder, respectively) with a powder base, e.g., MgO or CaO.

Grout technology can be tailored for a range of waste chemistries, available cement ingredients, and process, and final wasteform requirements. It can also be used to chemically bind certain radionuclides and hazardous contaminants by precipitation of low solubility phases, sorption on hydrated particle surfaces and / or incorporated into layer structures of the hydrated phases. Advantages of using grout technology to treat / condition waste include:

- Cements, mineral additives, and chemical admixtures are inexpensive and readily available
- Processing is simple and low-cost and occurs at ambient temperature
- Several remote processing options have been demonstrated and are available
- Cement matrix acts as a barrier to diffusion and fluid-flow and provides sorption and reaction sites, all of which can promote retention of waste
- Process is suitable for sludge, liquors, emulsified organic liquids and dry solids, as well as for a wide range of aqueous solution compositions
- Grout wasteforms have good thermal, chemical, and physical stability
- Alkaline chemistry of grout wasteforms promotes low solubility for many key radionuclides
- Grout waste-forms have good compressive strength to facilitate handling and to maintain stability of the disposal facility
- Grout formulations are flexible, allowing tailoring of mix-designs to meet particular wasteform requirements
- Grout processing options have been demonstrated for a wide range of waste volumes, from $>10^5$ L /day (saltstone) to <0.5 L batches
- Grout processing generates a minimum volume of secondary waste: the process incorporates water in the feed into the wasteform and the low temperature process minimizes contaminated HEPA filters needed to address off-gas from high temperature processes

The final properties of a grouted monolith depend on a number of factors, including dry-mix components and proportions, the ratio of dry-mix to water, the composition of the liquid waste, curing conditions and times, etc. In other words, grouts can have a range of final properties. The implications of this variability in the context of the present analysis include (i) improved retention characteristics for newer grout formulations (e.g., Cast Stone; mixes with getters; etc.) relative to grout formulations assumed in earlier assessments and (ii) the caution of using results of dry-mixes tested with liquid wastes that differ from those anticipated for SLAW.

Grouting technology has been designated as the best demonstrated available technology (BDAT) for LAW at the Savannah River Site (SRS), where it has been used to process over 17 million gallons liquid waste since 1991. The resulting wasteform is called saltstone. The waste feed solution for solidification in saltstone is currently decontaminated (Cs, Sr and actinide removal) in the Actinide Removal Process (ARP)/Modular Caustic Side Solvent Extraction Unit (MCU) prior to being transferred to Tank 50, which is the 1M gallon feed tank for the Saltstone Facility. Tank 50 is located in the H-Area tank farm about 1.6 miles from the saltstone processing facility, and salt solution is transferred from Tank 50 through a double jacketed line to a process feed tank in Z-Area. From there, it is transferred to the saltstone processing facility where the wastes are mixed with a blend of Portland cement, blast furnace slag (BFS), and class F fly ash (FA) in a ratio of 10:45:45 by weight. The dry blend is mixed with the liquid waste in a proportion of ~0.58–0.6 water:dry-mix (w:dm).

C.1.2 Cast Stone

Several dry-blend mixes similar to saltstone have been investigated for various Hanford waste streams, leading to a suite of specific products with favorable properties for specific wastes. Lockrem (2005a) presents a grout recipe that has favorable properties for Hanford's LAW streams: this recipe consists of dry blend ingredients in proportions similar to saltstone: 8 wt% OPC, 47 wt% BFS, 45 wt% FA, and it has been termed "Cast Stone". Other proportions of OPC-BFS-FA have also been investigated (e.g., Lockrem, 2005a; Sundaram, et al., 2011; Serne, et al., 2016), as have different water to dry-mix proportions (e.g., Westsik et al., 2013a; Serne, et al., 2016), and the use of various materials added to lower the mobility of technetium or iodine (referred to as "getters") (Qafoku et al., 2014; Crawford et al., 2017; Asmussen, et al., 2018). Other dry-mix components have also been investigated (e.g., hydrated lime; Serne, et al., 2016; Um, et al., 2016), but these have been for different waste streams so have not been tested with LAW; getters for Tc and/or I have also been tested for these other waste streams (e.g., Lockrem, 2005b; Saslow et al., 2017).

Hydration of Cast-Stone dry mix results in reaction products that include a range of phases. A suite of amorphous phases (including calcium silicate hydrate) dominate the reaction products, but ettringite and other crystalline alumino-ferrous sulfate phases have also been identified in hydration products from Cast Stone formulations (e.g., Sundaram, et al., 2011; Um, et al., 2016). Calcium hydroxide—which can occur in hydration of pure OPC—does not occur in the cast-stone system due to the addition of BFS and FA.

The formation of a grouted monolith results in a volume increase in the waste relative to the incoming LAW waste stream. In general, this volume increase is roughly ~1.8x; the actual volume increase will depend on the final mix design, w:dm ratio, etc. In addition, some pretreatment options could have small impacts to the volume of the liquid feed, which would then propagate into volume changes in the final grouted monolith. The details of these volume effects will depend on the process details, but these volume effects are unlikely to be significant.

The properties of monoliths made from Cast Stone formulations differ significantly from those made for Hanford LAW using earlier grout formulations that lacked BFS, particularly with respect to retention of many constituents of potential concern including at least some radionuclides. The addition of BFS to the dry mix alters the chemistry of Cast Stone, resulting in several characteristics favorable to Hanford's LAW streams. Blast furnace slag is activated by alkalis (Wu, et al., 1990), including the sodium sulfate and sodium hydroxide that are present in Hanford LAW; this results in a partial neutralization of high alkalinity of the LAW waste stream and improvements in the quality of the hydrated product such as lower permeability and higher long-term strengths (Wu, et al., 1990). Importantly, BFS imparts reducing conditions (low oxygen activity) to the final hydrated product, which significantly lowers the release for several elements including chromium, technetium, and uranium; recent experiments quantifying this effect are described in Appendix E.1.4. However, a central question remains: How does an initially reduced grout monolith oxidize under long-term disposal conditions, and how does this impact the long-term retention of redox-sensitive constituents?

Other mix designs have also been explored with constituents that differ from the basic Cast-Stone formulation; however, many of these have been designed to address waste streams with compositions that differ from the expected supplemental LAW feed vector. Um et al. (2016), Cantrell et al. (2016), and others present data on formulations developed for liquid secondary wastes, which have a composition distinctly different from LAW—for example, as Cantrell et al. (2016) note, the current liquid secondary waste stream is primarily a neutral-pH ammonium sulfate solution whereas the LAW feed vector is a sodium-nitrate, sodium-hydroxide solution with typically high pH. These alternative formulations used in combination with other waste streams could result in compositions and microstructures of the hydrated grout that differ from those found in Cast Stone formulations combined with LAW.

C.1.3 Availability of Cast Stone Materials

The materials used in the Cast-Stone formulation are readily available at present, and the materials needs for a Cast-Stone operation to handle projected volumes of SLAW is small compared with domestic production. As a rough guide, the materials needs to handle an 8 gallon per minute continuous feed of SLAW (i.e., continuous flow at maximum projected rates) for a Cast Stone mix are on the order of 0.004 million metric tons per year for OPC and 0.03 million metric tons per year for both BFS and FA.

In 2016, domestic production of Portland cement was roughly 85 million metric tons, and production from the 97 domestic kilns is well below capacity (USGS, 2017).

In 2016, domestic slag sales were 18 million metric tons, of which 47% was blast furnace slag (USGS, 2017); in addition, 2 million metric tons of slag were imported for consumption, primarily from Japan (33%), Canada (31%), and Spain (16%). The U.S. Geological Survey notes that domestic production of BFS continues to be problematic due to closure and/or idling of blast furnaces and the depletion of old slag piles; further, the demand for BFS may increase in some areas due to projected reductions in the supply of fly ash (USGS, 2017). Nevertheless, total BFS needs for a Cast Stone SLAW operation would be small with respect to domestic consumption. Hence, the current availability of BFS is not a barrier to a Cast-Stone operation for SLAW (i.e., annual needs for a SLAW operation would be less than a percent of the current domestic sales). Any concern over future uncertainties in availability could be addressed by stockpiling of BFS early in a SLAW operation and/or by investigating alternative feedstocks. It should be noted that BFS compositions and properties vary between sources, and this may impact the properties of Cast Stone monoliths (e.g., Westsik, et al., 2013a).

In 2016, total domestic fly ash production was 38 million short tons, of which 23 million short tons were used, primarily in the production of concrete and grout (ACAA, 2016a). Domestic production has steadily declined since 2010, while domestic use has remained constant (ACAA, 2016b). Total FA needs for a Cast Stone SLAW operation would be small with respect to domestic consumption. Hence, the current availability of FA is not a barrier to a Cast-Stone operation for SLAW (i.e., annual needs for a SLAW operation would be less than a percent of the current domestic production). It should be noted that fly ash varies in composition and properties depending on source, resulting in the broad categorizations of class F and class C (ASTM, C618-17a). Westsik, et al. (2013a) have shown that compositional variations with fly ash can impact the properties of Cast-Stone monoliths. Generally, class F fly ash—which has pozzolanic qualities—is used in Cast-Stone and saltstone formulations. Fly ash is generated during coal-based power production; to allay any concern over future availability of FA for Cast Stone, additional research may be warranted to assess the effectiveness of alternatives to FA—such as natural pozzolans.

C.1.4 Retention Characteristics of Cast Stone

A primary focus for the use of grout-based systems with Hanford low-activity waste has been whether the wasteform would perform sufficiently well with respect to retaining anionic species of radionuclides (particularly oxidized forms of technetium and iodine), because previous assessments of grouting raised concerns about the long-term retention of these species. (Retention of these species is not a concern for disposal at WCS, because grouted SLAW would comply with the waste acceptance criteria at WCS.)

Previous assessments—e.g., performance assessment, risk assessments, etc.—using data based on early grout formulations showed a level of release of radionuclides that could endanger groundwater (e.g., ^{99}Tc release predicted by Mann, et al., 2003). However, more recent studies have suggested that Cast Stone formulations have significantly better retention characteristics than earlier formulations—particularly with respect to Tc retention (e.g., Westsik, et al., 2013a; Cantrell, et al., 2016; Serne, et al., 2016; Asmussen, et al., 2018). Better performance with respect to iodine has also been observed in conjunction with the addition of silver-based getters (typically ion-exchanged zeolites) (e.g., Crawford et al., 2017). Hence, the FFRDC team considered these more recent studies and explored the implications of these studies on the retention characteristics of Cast Stone with respect to supplemental LAW.

These more recent studies report diffusion coefficients for Tc and I that have been determined by short term experimental methods—e.g., ANSI/ANS 16.1 (2003) or EPA 1315 (EPA, 2013). In this approach, the impacts of other processes that can affect retention (e.g., sorption, dissolution/precipitation) are assumed to be embodied in differences in the diffusion coefficients inferred for each species. It should be noted that some studies have suggested technetium and/or iodine may exist in phases other than the pore fluid, particularly for mix designs other than basic Cast Stone. For example, Saslow et al. (2017) report indirect evidence for the formation of Tc(IV) oxide phases in a grout formulation containing hydrated lime used with a liquid secondary waste; similarly, Asmussen et al. (2018) report formation of Tc(IV) oxide phases in LAW stabilized with Cast Stone formulations containing Sn(II) apatite and Tc(IV) sulfide species in LAW stabilized with Cast Stone formulations containing potassium metal sulfides. The incorporation of Tc and/or I into low solubility phases would significantly increase retention of Tc/I within the grouted wasteform and release would be more accurately described using a dissolution mechanism instead of an apparent diffusion coefficient. The analysis by the FFRDC team, however, did not attempt to resolve the retention mechanism but instead focused on the effective diffusion coefficient for the analysis (which may make the analysis somewhat conservative).

In the performance evaluation conducted by the FFRDC team (Appendix F), the calculations accounted for both advection (transport by a moving fluid) and diffusion. So, the effective diffusion coefficients reported in the recent experimental studies were re-cast as a diffusion coefficient coupled with a retardation factor (sometimes referred to as an apparent diffusion coefficient and distribution coefficient, respectively). This re-casting is consistent with the methodology used in formal performance assessments that have been conducted for the IDF (DOE, 2017). For details of the performance evaluation, see Appendix G. For clarity, the discussion that follows exploits effective diffusion coefficients in considering grout performance so that the dialog tracks with the experimental results reported in the literature.

The variation in measured diffusion coefficients for technetium is illustrated in Figure C-1, with the details on the various studies summarized in Table C-1 and shown graphically in Figure C-1. (These studies used Cast Stone made with low-activity waste; other studies of diffusion coefficients have also been conducted for Cast Stone made with secondary wastes.) The diffusion coefficients for Tc used by early assessments (e.g., Mann, et al., 2013 and TC&WM EIS, 2012) are significantly higher than those reported in more recent studies (e.g., Cantrell, et al., 2016; Serne, et al., 2016).

Table C-1. Summary of studies that report effective diffusion coefficients (cm^2/s) for Cast Stone made with low-activity waste.

Year	Technetium	Iodine	Nitrate	Notes	Source
1992	$7.7.0\times10^{-9}$ (DIW) 4.0×10^{-9} (HGW)	—	7.3×10^{-8} (DIW) 2.8×10^{-8} (HGW)	• DSSF waste stream • ANSI 16.1 test method • Deionized water and Hanford groundwater leachants • Water:dry-mix 1 liter:1080 gram	Serne et al. 1992. Waste Management 12:271-287
1995	2.1×10^{-7}	1.0×10^{-6}	—	• DSSF waste stream • ANSI 16.1 test method • degraded sample • Hanford groundwater leachant • Water:dry-mix 1 gal:8.4 lb (DIW) 8–9 lb (HGW)	Shade et al. (1995) WHC-SD-WM-EE-004, Rev 1
2003	3.2×10^{-10} ($0.8–6.3\times10^{-10}$)	2.5×10^{-9} (set to lower detection limit for iodine)	2.5×10^{-8}	• LAW SST Blend • ANSI 16.1 test method except 19-day (instead of 90-d) • Distilled water leachant **(???)** • Water:dry-mix 1 liter:1080g • Fracturing of grout did not have significant impact on releases	Mann et al. (2003) RPP-17675
	Individual values were "recommended" values based on 18.8 wt% TDS waste loading. Range for Tc corresponds to test range of 10.2–24.2 wt% TDS.			•	
2012	5.2×10^{-9}	1.0×10^{-10}	3.04×10^{-8}	• 10 M Na • 19-day test • Distilled water leachant • Ferrous sulfate monohydrate added • 18.8% waste solids	TC&WM EIS DOE-EIS-0391 (2012)

Table C-1 (continued). Summary of studies that report effective diffusion coefficients (cm^2/s) for Cast Stone made with low-activity waste.

Year	Technetium	Iodine	Nitrate	Notes	Source
2016	5.3×10^{-11}	5.7×10^{-9}	6.1×10^{-9}	• Average LAW; high sulfate; high Al; SST blend; 5 & 7.8 M Na • EPA 1315 test method; 63- & 91-day • Distilled water leachant • Water:dry-mix 0.4 and 0.6; multiple sources for FA, BFS	Cantrell et al. (2016) PNNL-25194 Based on Westsik et al. (2013a)
2016	5.96×10^{-12} (DIW; high Al) 7.55×10^{-13} (VZPW; high Al) 3.05×10^{-10} (DIW; SST blend) 3.02×10^{-11} (VZPW; SST blend)	—	—	• LAW; high Al & SST blend • 28–63-day average • Distilled water leachant; vadose zone pore water leachant • Water:dry-mix 0.6 (high Al) and 0.4 (SST blend)	Serne et al PNNL-24297 Rev1
2018	2.65×10^{-11} (DIW) 4.63×10^{-12} (VZPW) 1.73×10^{-11} (DIW; w/ KMS) 4.42×10^{-13} (VZPW; w/KMS)	—	—	• LAW; 6.5 M Na • 28–63-day average • Distilled water leachant; vadose zone pore water leachant • Water:dry-mix 0.55 • With/without potassium metal sulfide (KMS) Tc getter • 8.63 wt% loading	Asmussen et al PNNL-25577 Rev0

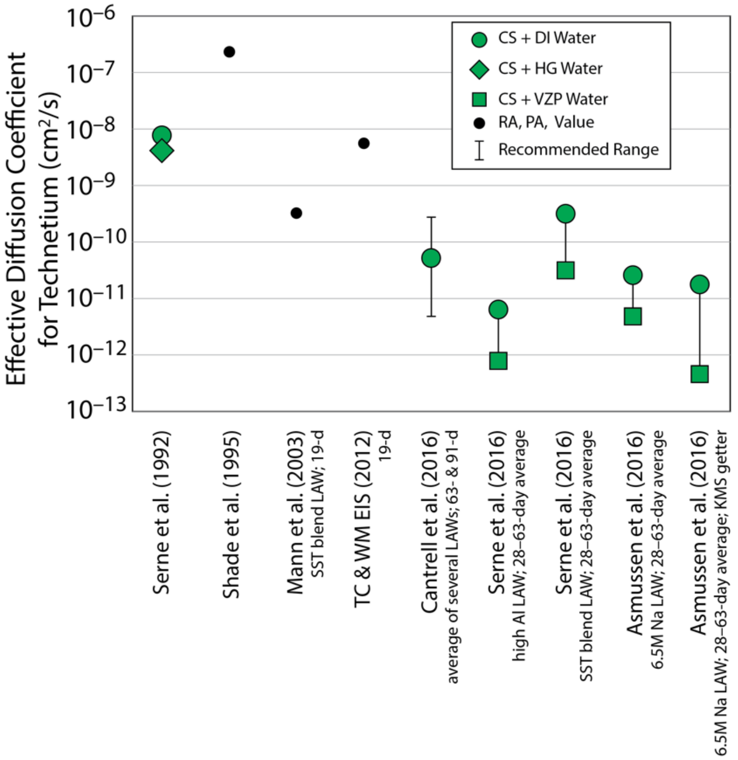

Figure C-1. Plot of effective diffusion coefficients for technetium in various grout-based wasteforms made from low-activity wastes. Additional details for each of the studies shown are provided in Table C-1.

Several factors impact the diffusion coefficients for Tc and likely account for these observed differences between earlier assessments and more recent studies:

- *Activity of oxygen*—Technetium solubility is highly sensitive to the oxidation state, with reduced forms of technetium being significantly less soluble than oxidized forms. Thus, at sufficiently low activity of oxygen, technetium release will be lower. Grout formulations containing blast furnace slag (BFS)—like Cast Stone and saltstone—will promote reduced forms of Tc.
- *Dry-mix ingredients*—The materials used in the dry mix for Cast Stone can impact the properties of the solidified grout. In addition to the reducing effects of BFS, other effects include the structure, composition, and morphology of the hydrated products in the wasteform, the microstructure of the wasteform, etc. Some dry mix materials—notably fly ash and blast furnace slag—may vary somewhat from source to source, which may or may not impact the characteristics of the final Cast-Stone product.
- *Water-to-dry-mix ratio*—The amount of water available for hydration impacts the microstructure of the final wasteform, including porosity. Saltstone formulations have used a water:dry-mix ratio of ~0.6 in order to maintain the pumpability of the slurry sufficiently long to allow the material to be pumped from the grout plant to the saltstone disposal units. Some studies have also investigated lower values of water:dry-mix (e.g., 0.4), which should result in lower porosity and, hence, better retention characteristics. In the semi-continuous batch process considered for the Hanford LAW, the FFRDC team assumed casting of the slurry in the grout plant, which could accommodate lower water:dry-mix ratios than are used for saltstone. However, optimization of the water:dry-mix ratio in a process must ultimately balance a number of additional factors including sufficient water for the hydration reactions and desired waste loadings.
    - *Low-activity waste composition*—The specific composition of the LAW used to make the Cast Stone can impact performance. Important factors include pH, sodium-ion content, and concentrations of sulfate, aluminum, etc.

- *Leachant used in diffusion-coefficient tests*—The conventional test methods used to determine diffusion coefficients (ANSI/ANS 16.1 and EPA 1315) use deionized water as the leachant in contact with the test materials. However, more recent studies have shown that the use of a leachant that is consistent with vadose-zone pore water at Hanford result in significantly lower estimates of diffusion coefficients for technetium. The effect of leachant composition is illustrated by the comparison of green circles and squares in Fig. C-1.
- *Duration of leach test*—Various durations have been used to determine diffusion coefficients. Recent studies have shown that estimates of diffusion coefficients evolve over the course of an experiment, with the inferred diffusion coefficient generally decreasing in the first couple of weeks. These observations suggest that different mechanisms for retention/release could operate at different time periods.

Figure C-2 illustrates some of the variation in measured effective diffusion coefficients for technetium due to the above factors, using data reported in Westsik et al. (2013a), which were the experimental data cited in Cantrell et al. (2016) (as shown in Fig. C-1). Several observations emerge from Figs. C-2:

- Effective diffusion coefficients derived from short duration experiments (e.g., <10 days) show a wider range than those determined from longer duration experiments. Generally (but not always) shorter duration experiments showed significantly lower effective diffusion coefficients. Accelerated test methods that rely on shorter duration experiments could emphasize short-lived processes that may operate early in an experiment over other processes that may dominate overall long-term performance.
- Effective diffusion coefficients at time periods >10 days show a spread of almost two orders of magnitude, due to a variety of factors that differ between the experiments, including sources of dry reagents, water:dry-mix ratio, LAW composition, and sodium molarity. This variation translates into an uncertainty in the effective diffusion coefficient. It also implies there could be an opportunity to tailor cast-stone formulations to optimize the performance.

In summary, effective diffusion coefficients for technetium based on recent studies suggest values for Cast Stone that are significantly lower than those used in earlier assessments. These lower values are anticipated to result in lower release rates for technetium, significantly improving the predicted performance. The FFRDC team attempted to assess this improved retention for Tc in a performance evaluation as described in Appendix F. This evaluation used a range of effective diffusion coefficients consistent with Fig. C-2 to represent a low performing grout (e.g., upper blue curve in Fig. C-2) and a high performing grout (lower blue curve in Fig. C-2). As detailed in Appendix F, the high performing grout is expected to retain Tc sufficiently well to protect groundwater. However, it should be noted that these recent studies are based on a limited set of lab-scale experiments, so additional research would be needed to document the implications of this improved retention of Tc relative to wasteform performance in IDF. (Documenting waste-form performance for grouted SLAW is not necessary for disposal at WCS.)

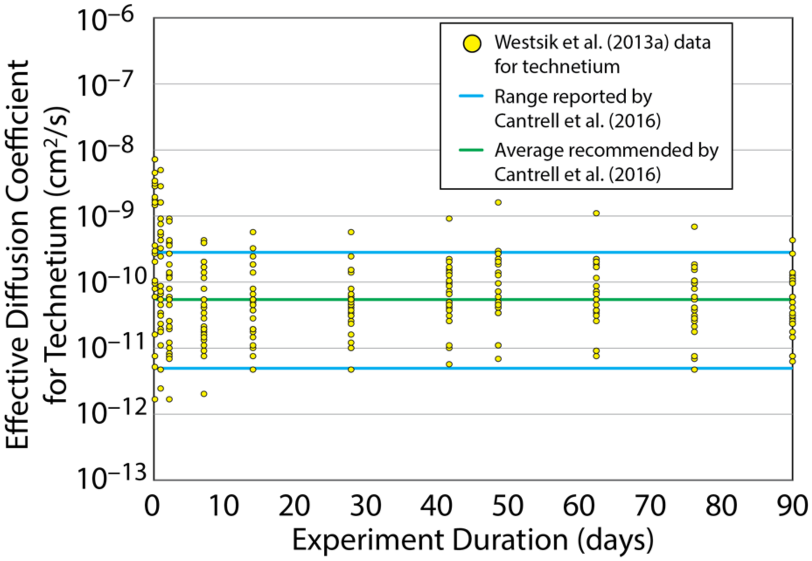

Figure C-2. Plot of effective diffusion coefficients for different durations of the experiment. Data show effective diffusion coefficients for technetium based on data in Westsik et al. (2013a), which were used by Cantrell et al. (2016) in developing recommended values for the Tc diffusion coefficient. The green line shows the recommended value given in Cantrell et al. (2016) and shown as a green circle in Fig. C-1. The blue lines show the range given in Cantrell et al. (2016) and shown as a bar in Fig. C-1.

Figure C-3 shows the trends for effective diffusion coefficients for iodine, also using data reported in Westsik et al. (2013a). Two observations emerge from the iodine data in comparison with the data for technetium: First, for iodine, the spread in effective diffusion coefficients is less that observed for technetium (only about an order or magnitude, comparable to the spread observed for nitrate in Fig. C-4). Second, iodine has a diffusion coefficient comparable to nitrate, which is generally believed to be unaffected by chemical retardation processes in these systems.

The available data on iodine are more limited than those for technetium (Table C-1), but they may suggest a slightly higher value for the effective diffusion coefficient than was used in earlier assessments, potentially approaching values for nitrate (which is assumed to diffuse without any chemical retardation effects).

The performance evaluation (Appendix F) used an effective diffusion coefficient consistent with the average value reported by Cantrell et al. (2016) (green line in Fig. C-3) to represent a low performing grout, and the low end value of Cantrell et al. (2016) (lower blue line in Fig. C-3) to represent a high performing grout. However, even the low blue line in Fig. C-3 did not result in iodine retention sufficient to protect groundwater, suggesting that Cast Stone formulations alone are not sufficient to retain iodine. Hence, to assess the performance of a projected best case grout, the performance evaluation considered retention characteristics consistent with the limited data available on Cast Stone augmented with iodine getters (typically based on silver zeolites) (i.e., Crawford et al., 2017; Saslow et al., 2017).

Recent studies (e.g., Qafoku et al., 2014; Crawford et al., 2017; Asmussen, et al., 2018) have shown potential for the use of special compounds (termed “getters”) that can bind Tc or I when used in combination with the Cast-Stone process to improve retention characteristics, perhaps by orders of magnitude. Although only limited investigation has been done on Cast Stone and LAW specifically, other studies using getters in combination with different grouts and different waste have found comparable levels of improved retention (e.g., Lockrem, 2005a; Saslow et al., 2017). Although limited data exist, the consistent results suggests that a strategy using getters could be developed to result in significantly increased retention of iodine in a Cast Stone monolith, reflecting the high performing grout case described in Appendix F.

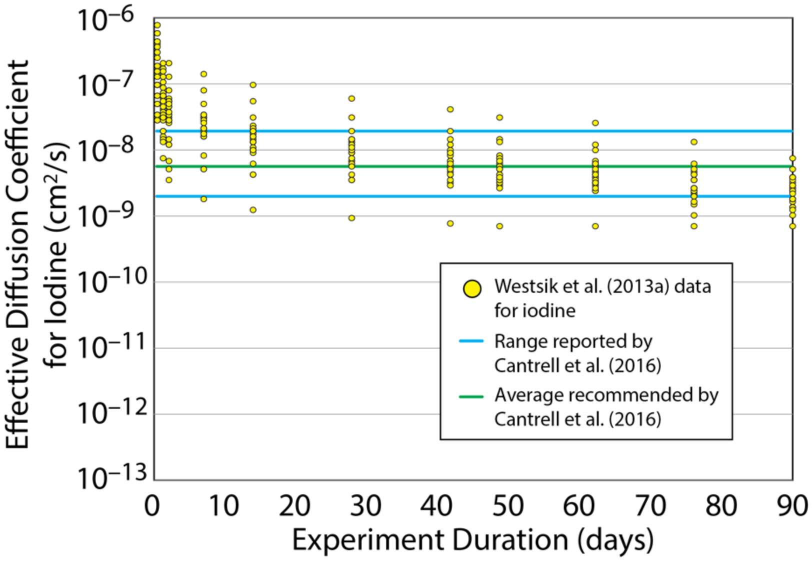

Figure C-3. Plot of effective diffusion coefficients for iodine for different durations of the experiment. Data show effective diffusion are based on data in Westsik et al. (2013a), which were used by Cantrell et al. (2016) in developing recommended values for the I diffusion coefficient. The green line shows the recommended value given in Cantrell et al. (2016), and the blue lines show the range given in Cantrell et al. (2016).

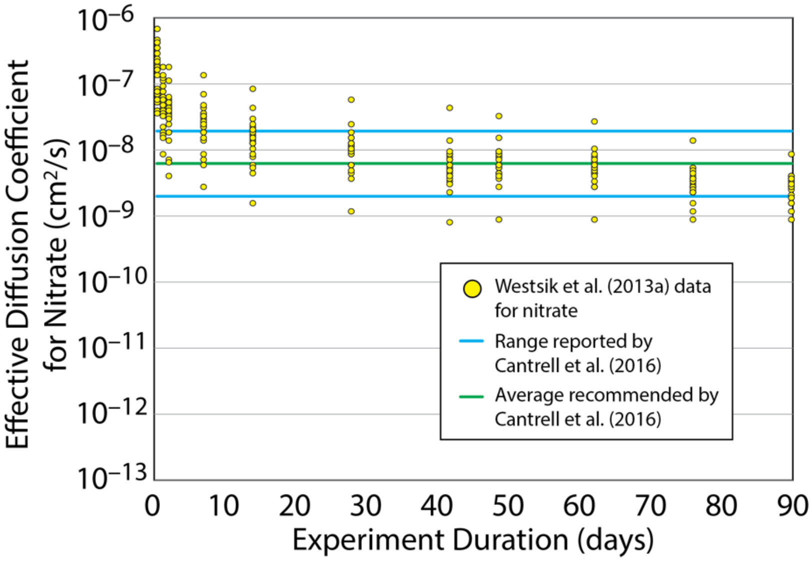

Figure C-4. Plot of effective diffusion coefficients for nitrate for different durations of the experiment. Data show effective diffusion are based on data in Westsik et al. (2013a), which were used by Cantrell et al. (2016) in developing recommended values for the I diffusion coefficient. The green line shows the recommended value given in Cantrell et al. (2016), and the blue lines show the range given in Cantrell et al. (2016).

C.2 DESCRIPTION OF FLOWSHEETS

All grout cases considered assume that low-activity waste has been processed by pretreatment associated with the Waste Treatment and Immobilization Plant (WTP-PT) and/or any pretreatment associated with the low-activity waste pretreatment system (LAW-PS).

In addition, any acceptable pathway for grout as a wasteform (either at IDF or WCS) will require addressing the potential presence of organics associated with land disposal restrictions (LDR) under RCRA. Hence, both primary grout cases assumed that the low-activity waste will be pretreated to comply with LDR associated with organic constituents and/or metals of concern. Addressing LDR concerns was viewed as a necessary component of any grout-based process, because the grout process does not inherently destroy organic compounds that may be contained in SLAW, so an additional treatment process may be needed to destroy these organics (e.g., by chemical oxidation). Some metals could also require an additional treatment step to ensure that the final wasteform passes the Toxicity Characteristic Leaching Procedure (TCLP); however, as noted below, Cast Stone formulations tested in laboratory experiments have successfully passed TCLP tests without the need for an additional treatment step for LDR metals. The need for treatment of LDR organics is detailed in section E.4.2.

Finally, all grout cases entail minimal secondary wastes, such that nearly all of the inventory of technetium and iodine reside in the final grouted wasteform. This low level of secondary waste ties, in part, to the low-temperature nature of the grout process, which does not volatilize technetium or iodine to be captured on HEPA filters associated with an offgas stream. Incoming aqueous fluids are incorporated into the grout process, as are secondary aqueous streams that might be generated during, for example, during flushing of the batch mixer.

C.2.1 Grout Case I (Disposal at IDF)

The grout case I process flow diagram considered in this assessment is shown in Figure C-5, which assumes disposal at the Integrated Disposal Facility (IDF).

The supplemental low-activity waste (SLAW) effluent is received into a 500,000 gallon tank for lag storage. This size tank is capable of accommodating roughly 40 days SLAW, assuming a constant input of 8 gallons per minute (maximum value anticipated in the current assessment).

The process is based on a Cast-Stone formulation for the grout, which consists of a dry-blend mix of 8 wt% ordinary Portland cement, 47 wt% blast furnace slag, 45 wt% fly ash (Lockrem, 2005a). Dry-mix silos are assumed to exist outside the grout plant footprint, allowing for the staging of dry ingredients; an additional silo is shown to note the ability to accommodate other mix ingredients as needed. Dry ingredients are fed to a blending tank prior to being introduced into the dry mix feed hopper.

Grout case I assumes a semi-continuous batch process, whereby a specified mass of dry-mix feed and SLAW are mixed as a single batch, which is then transferred to containers. The process could also be run in a continuous process, but the incorporation of a large lag tank storage would enable the use of a semi-continuous operation, providing flexibility on operational decisions (e.g., staffing, tailoring of mix designs as needed, etc.).

Containers are assumed to consist of a heavy duty polypropylene bag lining within an 8.4-m^3 steel box. This size and the use of a polypropylene bag were chosen to facilitate comparison between grout case I and grout case II (below); however, the exact container size and bag represent a minor factor in considerations of cost, process, and performance for grout case I. (The 8.4-m^3 size is compliant with disposal at WCS, which is considered in grout case II in Section E.2.2.)

The batch mixer is cleaned with water at the end of each batch, with the transfer of the resulting flush water to a storage tank where it can then be incorporated into the next batch.

Once the resulting Cast-Stone monoliths reach a specified curing stage, the grout monoliths are transferred to a lag storage and transport facility prior to shipment to the IDF for disposal.

A minimal amount of secondary wastes is anticipated in grout case I, and these were assumed to be grouted and transferred to the IDF. The details of the secondary waste disposition are not shown.

The technology readiness level for the grout case I process is estimated to be high (e.g., TRL 7-8) based on maturity of similar grout-based processes (e.g., SRS saltstone, etc.). However, as noted in Section E.1.4, the technical maturity of grout-based formulations relative to wasteform performance is lower, requiring additional research to verify recent lab-scale tests of improved leachability and to evaluate and document the implications of these results with respect to wasteform performance at the IDF.

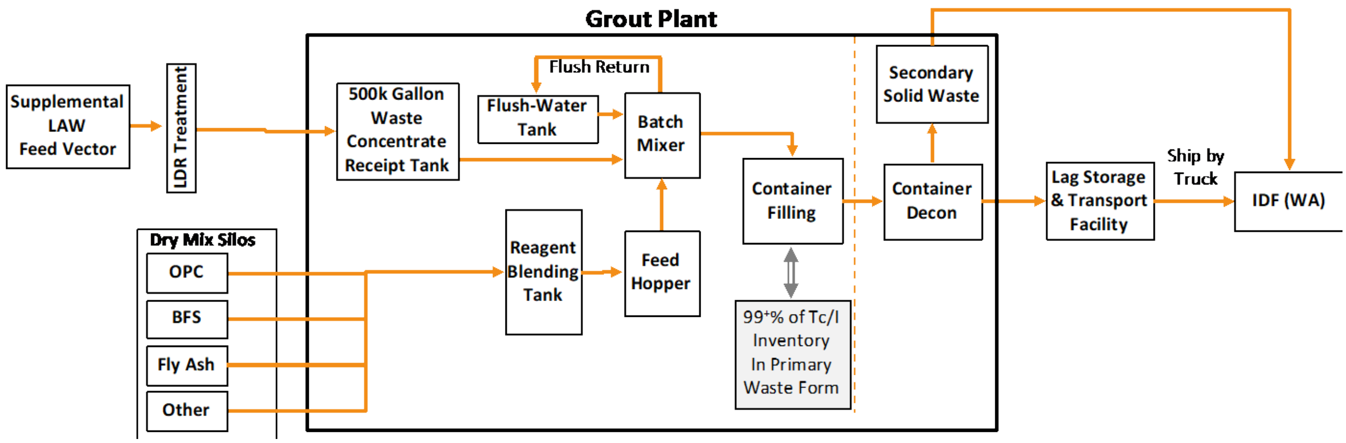

Figure C-5. Process flow diagram for grout case I, where the final Cast-Stone monoliths are disposed of at the Integrated Disposal Facility (IDF).

C.2.1.1 Risk-Mitigation Options for Grout Case I

Grout case I is predicated on the assumption that a grouted wasteform can be demonstrated to perform acceptably at IDF. A primary concern in this context is the ability to retain technetium and/or iodine such that groundwater protection is adequate. As noted in Section E.1.4, recent studies have suggested that Cast Stone formulations have potential for good performance characteristics with respect to Tc retention. Further, some studies have shown Cast Stone formulations augmented with silver-based getters have good retention characteristics for iodine. The performance evaluation by the FFRDC team suggests that these improved retention characteristics for Tc and I would be sufficient to protect groundwater. Nevertheless, additional research would be needed to confirm the improved retention of Tc and I relative to wasteform performance in IDF and to demonstrate the improved performance by incorporation of these results into a formal performance assessment. The potential for this research to be unsuccessful in demonstrating acceptability for a grouted LAW-containing waste at IDF represents a potential risk for grout case I. Figure E-6 lays out the risk mitigation logic for grout case I.

Mitigation for this risk could include adopting a pretreatment step to remove technetium (and, potentially, iodine). Technologies for technetium and iodine removal are discussed in Appendix B.3.2 and B.3.3, respectively. The technologies for technetium are generally at a medium TRL (4–6), whereas those for iodine are at a low TRL

(0–3). So additional R&D would be needed to mature the Tc removal process as applied to LAW waste streams, and significant R&D may be required to mature a removal process for I if needed. (As discussed in Appendix B.3.3, pretreatment for iodine removal was not considered in detail due to the very low TRL of this technology.) A pretreatment step for technetium would be incorporated prior to the LAW waste entering the grout facility, and the removed technetium could be sent to the high-level vitrification facility for incorporation with that waste process or it could be sent to the WCS facility (as discussed in Appendix B.4).

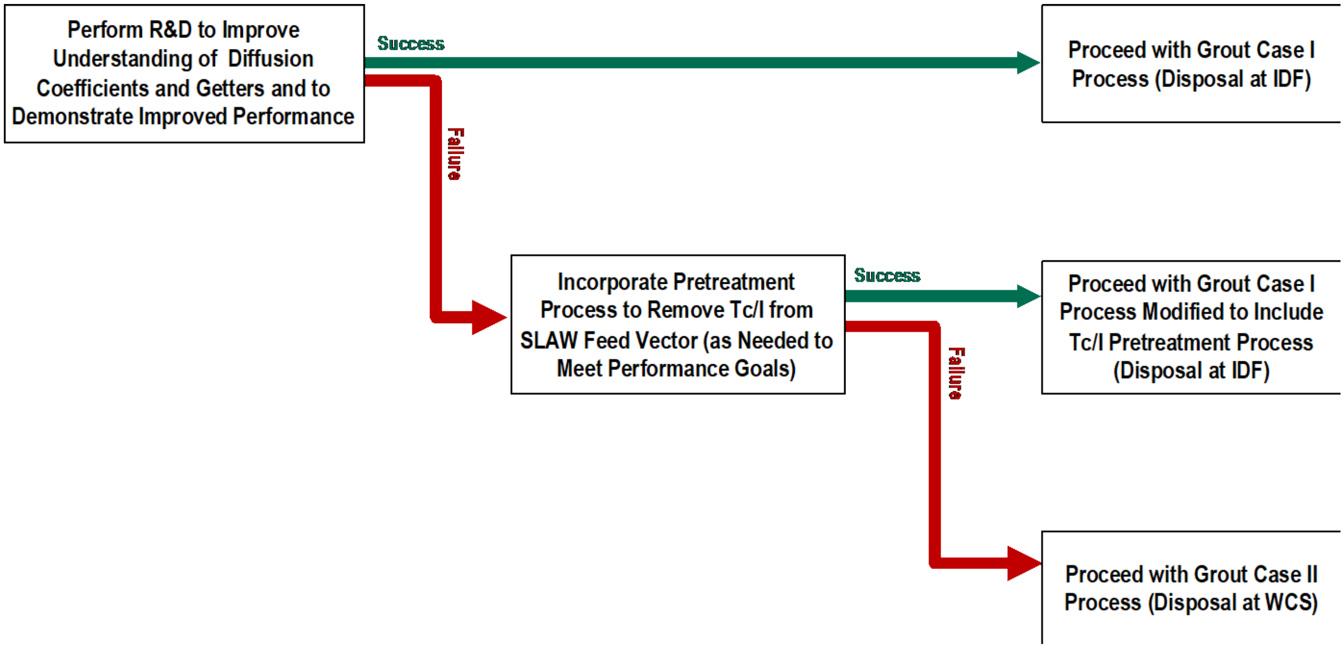

Figure C-6. Risk-mitigation logic for grout case I relative to primary risk associated with demonstrating acceptable performance for grout relative to retention of Tc/I.

A second mitigation strategy could be to send the grouted wasteform to the WCS facility for disposal, as discussed in case II (Section E.2.2).

E.2.1.2 Opportunity to Cast Grout Directly into Large Disposal Units

The saltstone process at the Savannah River Site casts grout directly into large disposal units (termed “saltstone disposal units or SDUs) constructed in the waste storage facility. The size of these units has evolved over time (~2–32 million gallons). The use of a large disposal unit similar to an SDU could improve both waste-form performance and costs, so it was considered as an opportunity in this assessment.

The process flow diagram for this opportunity would require locating of the grout plant near the final disposal site (presumed to be the IDF). Consequently, it would require installation of additional pipeline. However, the process would avoid the need for some components in the base case associated with containerization.

The potential improvements to the performance and economics would need to be evaluated quantitatively, which was beyond the scope of this assessment. A potential downside to LDUs is the inability to retrieve the wasteform should an issue arise with the curing of a particular batch.

C.2.2 Grout Case II Scenario (Disposal at the WCS Facility)

The grout case II process flow diagram considered in this assessment is shown in Figure E-7, which assumes disposal of the grouted monoliths at the Waste Control Specialists (WCS) facility in Texas. The WCS facility can accept Class A, B and C low-level radioactive waste, hazardous waste, and byproduct materials; thus, it can accept waste containing Tc and I at levels anticipated for SLAW without the need for removal and without the need to demonstrate a specific performance of the wasteform with respect to retention of Tc and/or I. Perma-Fix recently demonstrated the successful solidification, shipping, and receiving by WCS of a small volume (~3 gallons) of decontaminated Hanford waste stabilized with Cast-Stone.

The process flow for this case is similar to the grout case I process flow, with a few exceptions. Containers were assumed to consist of a polypropylene bag lining a reusable steel form; grout would be cast in the polypropylene bag and shipped to the WCS facility where the bagged, grouted monolith would be removed from the form and transferred to a disposal container at WCS. The steel form would then be returned to the grout facility at Hanford for re-use.

As with grout case I, the technology readiness level for the grout case II process is estimated to be high (e.g., TRL 7–8) based on maturity of similar grout-based processes (e.g., SRS saltstone, etc.) and the lack of a need for pretreatment for technetium or iodine.

The WCS facility can accommodate grouted SLAW wastes without any need for pretreatment to remove radionuclides. However, storage costs vary as a function of waste classification. Hence, there is an additional opportunity to lower costs for grout case II by incorporating a removal step for soluble strontium prior to LAW waste entering the grout facility. For example, a 99% reduction of strontium from the SLAW feed vector would result in a Class A grouted waste (as opposed to Class B), which could result in a $1B reduction in disposal costs at the WCS facility in Texas. Various processes for strontium removal are discussed in Section A-3.1; removed strontium would be sent to the high-level vitrification facility as noted in Section A-4.

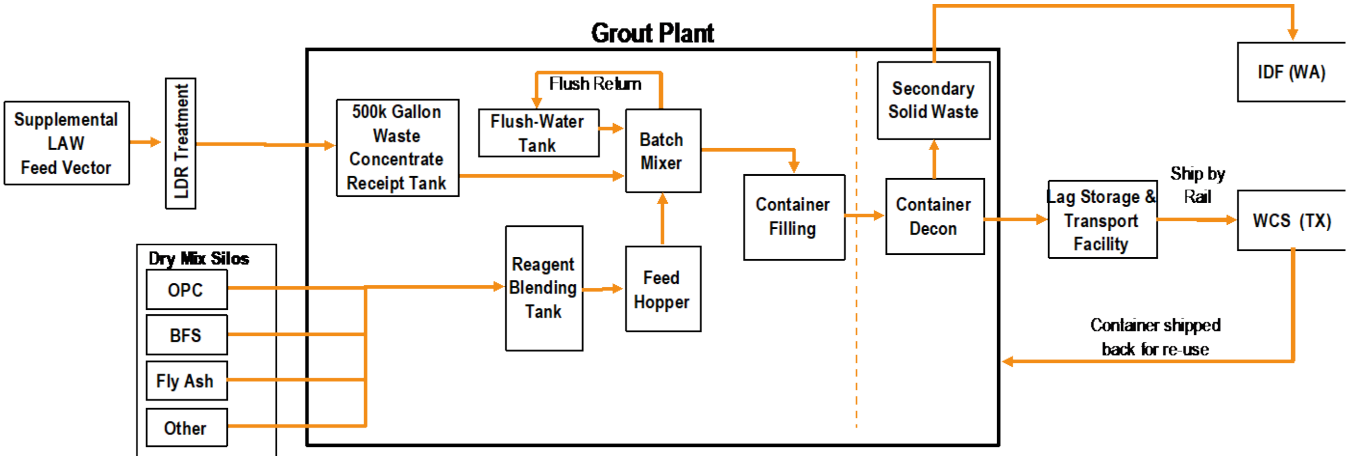

Figure C-7. Process flow diagram for the case II scenario considered for the grout process, where the final Cast-Stone monoliths are disposed of at the WCS facility in Texas.

C.2.3 Other Grout Options Considered

Several other cases were considered in the assessment before settling on grout cases I and II. Table E-2 presents a summary of the various cases considered during the analysis.

The initial base case considered in the assessment consisted of grouting SLAW with no pretreatment for LDR constituents associated with RCRA. The grout process does not inherently destroy organic compounds that may be contained in SLAW, so an additional treatment process is required to destroy these organics (e.g., by chemical oxidation). In addition, some metals could require an additional treatment step to ensure that the final wasteform passes the Toxicity Characteristic Leaching Procedure (TCLP). Since both IDF and WCS require compliance with LDR under RCRA, a grout process without LDR pretreatment was not considered as a final option. An alternative strategy could include selectively processing organic-bearing LAW in the LAW vitrification facility, using the grout process only for waste that does not require treatment for LDR organics. LDR metals can likely be handled successfully by grout.

Several additional cases were considered explicitly in the initial assessment, including cases with pretreatment for technetium, iodine, and/or strontium and a case in which grout is cast in a large disposal unit at the final storage location; process flow diagrams were developed and evaluated for each. Ultimately, the analysis was simplified into two primary cases (grout cases I and II), and these additional options were incorporated in the analysis as opportunities for cost savings or for minimization of project-risks within the primary cases.

Table C-2. Summary of cases considered in the assessment.

Final Label	**Interim Reference Label**	**Disposal Site for Primary Waste**		**Storage Container**		**Pretreatment**				**Notes**
		IDF	**WCS**	**10 m^3 block**	**LDU**	**LDR**	**Tc/I (sent to HLVIT)**	**Tc/I (sent to WCS)**	**Sr (sent to HLVIT)**	
	Base Case	X		X						Rejected—all disposal sites considered must comply with RCRA
Grout Case I	2d	X		X		X				
	2e1	X		X		X	X			Risk-mitigation option for grout case I
	2e2	X		X		X		X		Risk-mitigation option for grout case I
	2h	X			X	X				Alternative storage option for grout case I
Grout Case II	2g2		X	X		X				
	2f		X	X		X			X	Option for grout case II such that waste is class A to save costs

C.3 ASSUMPTIONS

The primary assumptions in the analysis of the grout process include the following:
- The ranges and averages in feed vector composition are adequately captured by the One System Integrated Flowsheet (Section 2.2 and Appendix L). This assumption impacted several aspects of the analysis, including size of facility, disposal volumes, compatibility of grout with the feed vector, potential need for pretreatment, etc.
- LDR organics are likely to be present in the SLAW feed. This assumption impacted the decision that pretreatment to destroy organics will be needed for any disposal site considered for grouted SLAW. As noted, an alternative strategy to address LDR organics could be to route any organics-rich LAW to the LAW vitrification facility, which would eliminate the need for an organics pretreatment step.
- Recent data showing lower values in release of Tc in Cast Stone formulations and lower values in release of I in conjunction with the use of silver-based getters reflect more accurate measures of expected diffusion coefficients than values used in earlier assessments. This assumption impacted the conclusion that grouted SLAW is likely to perform better than previously expected. This conclusion was in turn based on an additional assumption that research to confirm these new data on Tc/I release would have a high likelihood of success.

C.4 RISKS

C.4.1 Waste Acceptability

The acceptability of the wasteform was recognized as a potential risk with grout as an option for SLAW at IDF. Grout wasteforms have not been permitted for disposal at the IDF, and the State of Washington has explicitly questioned the use of a grout wasteform. This risk could potentially be mitigated in several ways:
- Additional R&D that demonstrates grouted SLAW complies with long-term performance goals at IDF
- The use of the WCS facility in Texas for the disposal of the grouted SLAW wasteform
- The removal (by pretreatment) of radionuclides of potential concern (Tc and I).

For all primary SLAW wasteform options (including vitrification and steam reforming), grout will likely be considered as a stabilization approach for any generated secondary wastes. If these wastes are destined for the IDF, waste acceptability represents a risk for all primary SLAW wasteforms, because grout is not permitted for disposal in the IDF.

In the case of additional R&D to demonstrate compliance with performance goals, this includes bench-scale R&D to improve the understanding of the retention characteristics of various wasteforms and extension of the results of this bench scale R&D to projected release over time in an IDF environment (i.e., a formal performance assessment). As detailed in Section C.1.4, several recent studies have shown the potential for a grouted wasteform to retain technetium and iodine (with getters) under some conditions.

Westsik et al. (2013a) and the subsequent extended set of tests reported in Serne et al. (2016) investigated the release of various constituents including technetium and iodine as a function of potential factors that could impact their retention. The studies present a more comprehensive range of effective diffusion coefficients for technetium and iodine in a Cast-Stone matrix than earlier studies, suggesting that iodine behaves comparable to nitrate (a non-chemically retarded species in these systems) and that technetium is released at a rate lower than previous assessments assumed. Nevertheless, these studies leave several issues unaddressed that would be needed to demonstrate waste acceptability, including:

- Testing over a comprehensive range in LAW chemistry consistent with ranges anticipated in the feed vector. Westsik et al. (2013a) did include a high sulfate LAW composition (which captures most of the feed vector range), but variations in other constituents should also be considered as should appropriate waste loadings.
- Testing of dry mix constituents in a manner to elucidate causes in observed differences in effective diffusion coefficients. This is particularly true for technetium, which showed a 100x variation in the screening tests. Understanding the cause of this variability would allow optimization of mix designs for maximum retention.
- Testing to assess rates of oxygen ingress into Cast-Stone monoliths and its impact on technetium release rates.
- Testing to assess the effectiveness of iodine getters in conjunction with Cast Stone formulations over a comprehensive range in LAW chemistry consistent with ranges anticipated in the feed vector. Testing to identify other potential iodine getter formulations/materials (e.g. bismuth-based as Ag is a RCRA listed metal).
- Testing to assess the potential impact of the process to address LDR organics on the performance of the grouted wasteform.
- Use of new effective diffusion coefficients to update predictions of performance in an IDF environment.
- Testing of a range of alternative substitutes for mix design components with uncertain future availability (as noted below under C.4.3).

This need for additional work leaves waste acceptability as an outstanding risk for the choice of grouted LAW at IDF—i.e., the risk that the additional R&D would not demonstrate waste acceptability. (This risk does not apply to disposal at WCS, where grouted waste with Tc and I are already permitted.) A mitigation strategy for this risk could include the adoption of a technetium pretreatment step or the disposal of grouted LAW at WCS, where the technetium and iodine content are permitted.

C.4.2 LDR Constituents

Any acceptable pathway for grout as a wasteform (either at IDF or WCS) will require addressing the potential presence of organics associated with LDR under RCRA. Grouted wasteforms have been shown to be BDAT for some LDR metals, and laboratory-scale tests on Cast Stone formulations have been shown to pass TCLP for at least some LAW chemistries. However, the LDR organics are not addressed by a low temperature grout process. This is a risk that can be mitigated by inclusion of an organics treatment step in the process (e.g., degradation by oxidation). This treatment step would remove or destroy organics prior to the SLAW feed entering the grout facility, and it is assumed to be incorporated in both primary grout cases considered (Sections C.2.1 and C.2.2).

Developing and demonstrating an effective pretreatment process for LDR organics in the context of a grout process remains an area for additional work. As noted in Section B.2.4, this is challenging in part due to uncertainty in the characteristics of the feed vector, particularly relative to the types and amounts of organics species that may need to be treated; this information is needed to make a final determination of the required treatment specifications. One possible strategy is to divert any SLAW feed that contains organics of concern to the LAW vitrification facility. Alternatively, an organics pretreatment process could be incorporated prior to the SLAW entering the grout facility. Section B.3.4.1 discusses some organics management methods, but these would need to be demonstrated on the SLAW waste streams, and it would need to be demonstrated that the pretreatment method does not deleteriously impact the retention characteristics of Cast Stone. This leads to two risks associated with LDR organics:

- A feasible/effective process to destroy LDR organics cannot be identified/developed. This risk applies to both IDF and WCS.

- The process to destroy LDR organics impacts the performance of the grouted wasteform, which may be a particular concern for technetium. This risk is addressed above in the recommendations for additional testing in Section E.4.1. This risk applies to IDF only.

Any acceptable pathway for grout as a wasteform (either at IDF or WCS) may also require addressing the potential presence of some metals associated with LDR under RCRA. A treatment step could be included if there is a concern that final wasteforms would not pass TCLP. This treatment step would remove metals of concern prior to the SLAW feed entering the grout facility, as considered in Sections A5.3.1.2 and A5.3.1.5.

C.4.3 Other Potential Risks Applicable to All Grout Processes Considered

Other potential risks for selection of grout as an option include:

- *Future unavailability of reagents.* This risk is discussed in Section A5.3.0.2, and it primarily ties to blast furnace slag and fly ash. BFS limitations can be mitigated through imports (for example from Canada or Japan). FA limitations can be mitigated through the identification and certification of an alternative material, such as a natural pozzolan (e.g., a Class N material, as identified in ASTM C618). This risk was evaluated to be low because the materials needs are very low (<1%) relative to current domestic production. The risk could be mitigated by several strategies as noted, and also including for example stockpiling of materials with appropriate properties. In addition, research on substitute materials could be considered as an anticipatory measure for blast furnace slag and fly ash
- *Construction and start-up testing of a facility will not be met within budget or timeline.* This risk was evaluated to be low due to extensive experience constructing similar facilities (i.e., DOE's grouting experience) and based on it being a simple facility/process (ambient temperature, minimal offgas, commercially available reagents)
- *Inability to mature a specific aspect of the process to a high TRL within time.* This risk is most applicable to new formulations such as the use of getters for Tc and I. This risk was evaluated to be low due to relatively simple modifications needed to incorporate new formulations into the process and due to the existing body of testing on various formulations

Potential risks associated with the operational phase of a grout process include:

- *The inability of a specific batch to meet acceptance criteria.* This risk, for example, could relate to an improperly proportioned batch and/or a batch with a composition outside of specifications resulting in a failure to set, low strength, bleeding, etc. This risk was evaluated to be low because this outcome is readily addressed with existing technology, whereby the monoliths could be identified in the lag storage facility and subsequently processed by grinding and re-grouting. In addition, adjustments to mix proportioning can be used to account for waste variability, thereby minimizing the likelihood of a poor batch.
- *Insufficient capacity at the waste storage facility.* This risk was evaluated to be low because the existing facilities have capacities larger than the projected waste volume from a SLAW grout process, and adjacent land is available at WCS, in particular, for expansion. The exact waste volume will depend on design of a packing strategy for the storage operation, which was beyond the scope of the current assessment.

C.5 BENEFITS AND COST ESTIMATE

Many of the benefits of grout as an option to address supplemental LAW stem from the fact that grouting is a non-thermal process. As such, several specific benefits include:

- Least-complex process of three options considered
- Ambient temperature process
    - Elimination of potential worker safety concerns associated with high temperature processes

- Minimal offgas, hence less solid secondary waste.
- Lowest secondary waste volume due to minimal offgas treatment and no liquid secondary waste stream
- Start/stop flexibility, which can accommodate variations in feed-vector

It should be noted that one potential downside of the relatively low temperature aspect of grouting is that organics that may be in the waste stream are not inherently thermally destroyed.

Cost estimates for the grout process are detailed in Appendix J. Grout has the lowest estimated costs among the options evaluated, ranging from ~$2B to ~$8B for Grouting Cases I (IDF) and II (WCS), as shown in Tables C-3 and C-4.

Table C-3 Estimated costs ($M) for Grouting Case 1

Grouting Case 1	**Low End**	**Analog Estimate***	**High End**	**Comments**
Technology Development	90	-----------------------	200	Set at 18% of TPC
Pilot Operations		-----------------------		See Note 2.
Total Project Cost (TPC)	500	560	1120	(-10% / +100%)
Operations (OPEX)	1120	1400	1680	(-20% / +20%)
Major Equipment	130	-----------------------	280	Set at 25% of TPC (Note 3)
Total Program Cost	1850		3280	

*The analog selected for grouting was SRS Saltstone. See Appendix H, “Cost Estimate Methodology and Results.”
Grouting costs note 1: Values are rounded.
Grouting costs note 2: Pilot is not recommended. No expected efficiency gain/impact to SLAW grout.
Grouting costs note 3: Based on SME input and Saltstone experience.

Table C-4 Estimated costs ($M) for Grouting Case 2

Grouting Case 2	**Low End**	**Analog Estimate***	**High End**	**Notes**
Technology Development	120	-----------------------	260	
Pilot Operations		-----------------------		
Total Project Cost (TPC)	650	720	1440	(-10% / +100%)
Operations (OPEX)	1120	1400	1680	(-20% / +20%)
Major Equipment	160	-----------------------	360	Set at 25% of TPC
Off-Site Trans/Disposal	2780	-----------------------	4163	SME Quote / 150% Quote
Total Program Cost	4820		7900	

*The analog selected for grouting was SRS Saltstone. See Appendix H, “Cost Estimate Methodology and Results.”

C.6 SCHEDULE

For the grout process, the estimated time to complete additional R&D, design, construction, and cold start (i.e., to hot start up) is 8–13 years (see Appendix H for details).

C.7 REGULATORY COMPLIANCE

Details on regulatory compliance are provided in Appendices K (general), G (specific considerations for IDF and WCS), and H (transportation related).

Based on the feed vector, all grouted supplemental LAW would not exceed the applicable concentration limits for Class C low-level waste as set out in 10 CFR 61.55. In fact, it is estimated that most of the waste (408 months) would be classified as Class B low-level waste and only 33 months would result in Class C (Appendix G.5.4.3).

Based on the feed vector, all grouted supplemental LAW readily meets criteria needed to ship the waste as LSA-III (Appendix H.4).

Disposal at both IDF and WCS require compliance with LDR under RCRA. Although grout has the potential to address LDR metals (e.g., by demonstrating that wasteforms pass TCLP), organics are not inherently destroyed by the grouting process. Hence, some process considerations—e.g., pretreatment to destroy organics, or re-routing of organic-rich wastes to LAW vitrification—may be needed. Alternatively, recategorization of the waste (as discussed in Appendix K.4) may allow a re-determination of the need to address LDR organics.

With respect to waste acceptance criteria, grout complies with the WAC for the WCS facility, which has a Federal Waste Disposal Facility licensed to accept Class A, B, and C low-level waste and mixed low-level waste; the licensed volume is 736,000 m^3 (G.5.2), whereas the projected volume of grouted supplemental LAW would be ~370,000 m^3. Grouted supplemental LAW is not currently permitted at the IDF facility.

C.8 OBSTACLES

Obstacles for grout as an option to address SLAW include:

- Organics subject to LDR remain in grouted wasteform.
- Grout is not permitted at IDF. This obstacle applies only to disposal at IDF (Grouting Case I).
- Acceptable grout performance needs to be demonstrated. This obstacle also applies only to Grouting Case I (disposal at IDF). Demonstration of acceptable grout performance would require (i) conducting additional R&D to confirm Tc/I retention properties of new grout formulations, and (ii) conducting a formal performance assessment using updated retention characteristics applicable to new grout formulations.
- Highest volume primary waste.

C.9 AREAS FOR FURTHER ANALYSIS

As noted above, there are several areas that could warrant further analysis for the grout process:

- *Strategies for LDR Organics.* A detailed assessment of likely levels of organics over time in the feed vector (types and amounts) could improve assessment of whether a pretreatment process is needed or whether alternative strategies (such as sending specific parts of the feed vector to the LAW vitrification facility.
- *Pretreatment Options for Organics.* Should a pretreatment process be needed for organics, additional analysis would be needed on types of pretreatments that could reliably address LDR concerns without impacting the effectiveness of Cast Stone relative to retention of radionuclides.
- *Improving the Understanding of Factors That Impact Cast Stone Performance.* As noted, retention of constituents of potential concern exhibits a range in experimental studies, with a spread of ~10x for iodine and nitrate and a spread of ~100x for technetium. A better understanding of the cause of this spread would improve the analysis of expected performance and could lead to optimized performance. Included in this category could be the impact of additives that specifically sorb Tc or I (getters).

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APPENDIX D. STEAM REFORMING

D.1 INTRODUCTION

Fluidized bed steam reforming (FBSR) has been researched, developed, and used commercially for over two decades for processing low level radioactive wastes. The commercial Erwin Resin*Solutions* Facility (formerly Studsvik Processing Facility) in Erwin, TN began operation in the late 1990s to treat radioactive wastes such as ion exchange resins with contact radiation levels of up to 100 R/hr (Mason 1999, http://www.energysolutions.com/waste-processing/erwin-resin-processing/). Small-scale FBSR testing for treating liquid, highly acidic, radioactive sodium bearing waste (SBW) stored at the Idaho National Laboratory (INL) was also initiated in 1999. FBSR research and demonstration tests have been expanded since then from a nominal 3.5 in. diameter to most recent 24-in. diameter tests at Hazen Research Incorporated (Hazen or HRI) using non-radioactive simulants, and also bench-scale tests at Savannah River National Laboratory (SRNL) using actual radioactive Hanford LAW and radioactive-shimmed simulants.

The properties and performance of the FBSR product depends on the objectives of the treatment process. In the case of the Integrated Waste Treatment (IWTU) at Idaho National Laboratory (INL), the goals include destroy nitrates, destroy organics, and convert the liquid sodium bearing waste (SBW) into a solid granular material that does not need to be a durable, leach-resistant wasteform. The IWTU produces a quite water-soluble sodium carbonate-based solid granular product that is not a durable, leach-resistant wasteform. In the case of Hanford SLAW treatment, the goal indeed is to produce a durable, leach-resistant wasteform, which FBSR has been shown to achieve using the needed design and operation.

D.1.1 Durable, Leach-Resistant Mineralized Na-Al-Si Wasteform

Multiple bench and pilot-scale mineralizing FBSR research and development programs for treating various liquid radioactive wastes have been performed between 2001 and 2011 and summarized in a report for the multi-laboratory SRNL, Oak Ridge National Laboratory [ORNL], Pacific Northwest National Laboratory [PNNL], and Washington River Protection Solutions [WRPS] mineral wasteform performance test program downselection studies [Jantzen 2015]). Studsvik, Inc. has also continued to develop and demonstrate steam reforming for various world-wide customers including ORANO (formerly AREVA). Various additional references for specific bench and pilot-scale mineralizing FBSR test programs include: Marshall 2003, Olson 2004a, Olson 2004b, Soelberg 2004a, Soelberg 2004b, Studsvik 2004a, Studsvik 2004b, TTT 2007a, TTT 2009a, and TTT 2009b.

The durable, leach-resistant mineralized Na-Al-Si wasteform is the intended wasteform for FBSR treatment of Hanford SLAW.

D.1.2 Sodium Carbonate-Based Product

Steam reforming has also been developed and demonstrated to produce a granular carbonate-based product; that, while treated to destroy nitrates and organics and eliminate the liquid component of INL's SBW is not intended to be leach-resistant. Indeed, the carbonate product is quite (typically over 50 wt%) soluble in water.

The IWTU was designed and built at INL to treat the liquid SBW presently stored in tanks at INL, and produce a sodium carbonate-based product. The IWTU is currently in non-radioactive startup operations to make it ready to begin SBW treatment. The IWTU is a first-of-a-kind (FOAK), full-scale demonstration of steam reforming technology and processes. However, the highly soluble carbonate product does not represent the intended Na-Al-Si wasteform that can be produced from the Hanford SLAW.

Any implication that the Na-Al-Si wasteform for FBSR treatment of Hanford SLAW is highly soluble, because the IWTU carbonate product is highly soluble, is not correct.

D.2 MINERALIZING FLUIDIZED BED STEAM REFORMING PROCESS

Steam reforming is a process in which superheated steam is used to crack and pyrolyze organic constituents, which in turn generates intermediate species that can destroy nitrates in the WF, and convert the liquid WF into a solid product. Radioactive liquid wastes such as Hanford LAW that contain dissolved nitrate/nitrite salts, mineral acids, alkali hydroxides, or residual organic solvents are candidates for steam reforming. The liquid waste is sprayed through the side wall of the DMR vessel, which contains a fluidized bed heated to nominally 725-750^{o}*C.*

The fluidized bed is maintained at nominally 725-750^{o}C by preheating the incoming fluidizing steam to about 600^{o}C, and through the oxidation of coal added to the fluidized bed. The coal reacts with steam and added oxygen to (a) heat the DMR to the target operating temperature, and (b) produce H_2 and other reduced gas species such as CO and CH_4 that react with the nitrates in the waste feed (WF), converting the nitrates and nitrites to N_2 and H_2O. The coal and O_2 feedrates are metered so that the overall DMR process is stoichiometrically reducing to pyrolyze and destroy hazardous feed organics and achieve efficient NO_x destruction on the order of 95-99%, with small residual amounts of reduced gas species including H_2, CO, and hydrocarbon gas species in the DMR outlet gas. Fluidized beds with liquid waste feed, fluidizing gas, and solid feed inputs require rigorous process monitoring and control to ensure (a) efficient waste feed injection that atomizes and rapidly mixed with the bed particles, (b) fluidizing gas distribution and mixing to ensure complete fluidizidation, (c) temperature and stoichiometry control to ensure destruction of nitrates, organics, and ammonia compounds, and product mineralization, and (d) bed particle size control.

The WF is premixed with kaolin clay prior to being fed as a slurry into the DMR. Kaolin clay reacts with the WF in the DMR and converts the DMR product into a durable, leach-resistant wasteform. Kaolin clay is commercially available and widely used in industrial and commercial uses such as manufacture of porcelain fixtures. The resultant mixture is a liquid-solid slurry because the clay does not appreciably dissolve, although some mineralizing reactions can be initiated even at room temperature in the clay-waste mixture (Lorier 2006). The mixture has a consistency similar to an ice cream milkshake.

The WF slurry is atomized using air or N_2 atomization through the vessel wall directly into the hot fluidized bed. The atomized WF evaporates in less than 1 second as the WF heats to and beyond 100-120^{o}C. With continued rapid heating, the nitrates decompose and organics pyrolyze, react with each other or other reducing or oxidizing species, and become gasified reaction products N_2, CO, CO_2, hydrocarbon gases, and H_2O.

A large variety of heterogeneous solid-gas and homogeneous gas-phase reactions occur during fluidized bed steam reforming (Soelberg 2004a and the SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015]). These include NO_x reduction reactions; coal, oxygen, and steam reactions that produce energy to heat the DMR, evaporate water in the WF, and provide H_2 and other gas species that reduce NO_x; and waste organics pyrolysis reactions. These reactions occur rapidly in a fluidized bed because the gas:solids mixing and high solids surface areas encourage high mass and heat transfer rates and improve overall reaction kinetics. The DMR outlet gas contains nominally on the order of 65-70 vol% H_2O; 10-15 vol% CO_2; 10-15 vol% N_2; 1-3 vol% H_2; 1 vol% CO; 0.5-1 vol% NO_x; <0.1 vol% hydrocarbons; and <100 ppmv other gas species such as SO_2 and halogen gases.

The dissolved and undissolved components of the SLAW (including Na, Al, and other elements including hazardous metals and radioactive elements) react with the clay to form the target mineralized wasteform. These reaction products coat existing bed particles or form new bed particles. The mineralized product can exit the DMR when bed particles are removed from the DMR using an auger/grinder system, or when fines elutriate from the DMR with the process gas, and are captured in the Process Gas Filter (PGF).

D.2.1 DMR Design and Operating Features

These reaction processes are aided by the design and operation of the fluidized bed:

- Haynes 556 alloy or equivalent for strength and corrosion tolerance at temperatures ~725-750°C (a refractory-lined vessel could also be used depending on detailed design).
- Preheated steam, O_2, and N_2 fluidizing gas flows up from the bottom.
- Heated by coal oxidation with sufficient excess coal for stoichiometrically reducing conditions and temperature to destroy WF nitrates, nitrites, and organics.
- N_2, O_2, or air – atomized liquid/slurry WF nozzles.
- Granular solid product removed from bottom.
- Gas discharge out the top.
- Sealed thermocouple ports.
- Pressure ports penetrate through vessel wall and are N_2-purged to keep clear of bed particles and prevent moisture condensation.
- Exterior is insulated (not shown) as needed for heat retention.

Figure D-1 illustrates the main features of a fluidized DMR vessel.

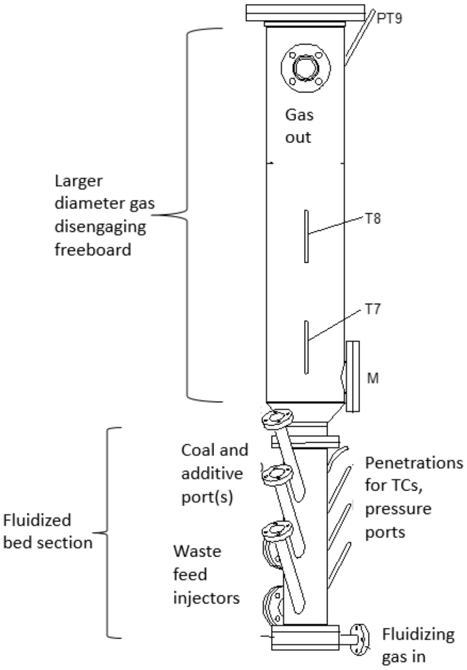


Figure D-1. Illustration of a fluidized DMR vessel (from Olson 2004a).

While this exemplifies the primary features of the fluidized bed vessel, the actual design for Hanford SLAW treatment would be based on Hanford SLAW treatment system requirements. Specific features including operating temperature, size, throughput rate, feed injection design, fluidization distributor design, and product properties would be designed specifically for Hanford SLAW treatment.

D.2.2 How Fluidized Bed Steam Reforming Would Treat Hanford SLAW

The SLAW treatment system feed vector varies widely and presents flowrate and composition challenges for the SLAW treatment process. Table D-1 summarizes monthly feedrate and composition data along with the “turndown ratio” that is used to describe the month to month variability. The monthly feedrate turndown ratio is the ratio of the maximum monthly flowrate divided by the minimum monthly flowrate ratio. The feedrate and the turndown ratio causes the need for (a) at least two FBSR systems to operate in parallel to maintain SLAW processing at average minimum rates even when one is off-line for maintenance, and (b) additional WF delay storage to reduce the monthly turndown from over 50x to about 2x for each FBSR system.

Table D-1. SLAW treatment system feed vector monthly feedrate and composition data.

Parameter	**Monthly average**	**Monthly turndown ratio (max/min)**	**Comments**
SLAW feedrate, gpm	3.6	**51**	High turndown ratio; delay storage reduces variation
WTP LAW feedrate, gpm	3.4	1.8	Steady flowrate presumably by design
Solids concentration, wt%	3.3	126	Not relevant to FBSR which has much more added clay
Na concentration, g/L	180	2	Vary clay as needed
NO_3 concentration, g/L	110	6	Destroyed by FBSR system
NO_2 concentration, g/L	30	11	
Hg concentration, mg/L	3.0	55	Need Hg control but necessary DF decreases after ~2035
Tc-99 concentration, mg/L	3.2	36	Captured in product due to their relatively high capture efficiencies and recycle of scrub solution to the DMR; no liquid secondary wastes
I-129 concentration, mg/L	0.3	16	
S concentration, mg/L	56	470	
Organics, NH_4 concentration	Destroyed by FBSR system		
The turndown is the ratio of the maximum monthly flowrate (or concentration) divided by the minimum monthly value.			

D.3 FBSR PROCESS OPTIONS AND DIAGRAMS

Three FBSR options are proposed, based on the desired wasteform. Steam Reforming Case 1 (Figure D-3), provides a durable, mineralized wasteform for storage and permanent disposal in the Hanford Integrated Disposal Facility (IDF). A geopolymer process downstream of the FBSR converts the granular FBSR product to a monolith, needed to meet the expected IDF 500 psi compressive strength limit. The monolith is prepared and poured into a suitable-sized disposal bag contained inside a steel storage/transport box, which provides rigidity while the geopolymer cures, and physical protection from damage during temporary storage and transport to IDF. After transport to IDF, the bag containing the solidified geopolymer is removed from the re-useable box, and placed in the IDF. The box is then available for the next batch. Secondary wastes in this option (spent filters, equipment, PPE, etc.) are grouted inside B-25 boxes for disposal in IDF in the same way that they would be for vitrification.

Secondary wastes in this option (spent filters, equipment, PPE, etc.) are disposed in IDF.

Case 2, Steam Reforming to WCS (Figure D-4) excludes the geopolymer monolith process, because WCS does not have a compressive strength limit. Secondary wastes in this option (spent filters, equipment, PPE, etc.) are also disposed in WCS. Alternative Option 3c (Figure D-5) features disposal of the granular wasteform at IDF inside concrete high integrity containers (HICs) to meet the IDF compressive strength limit without the added geopolymer process. Secondary wastes in this option (spent filters, equipment, PPE, etc.) are also disposed in IDF. Option 3c was not evaluated in detail in this study.

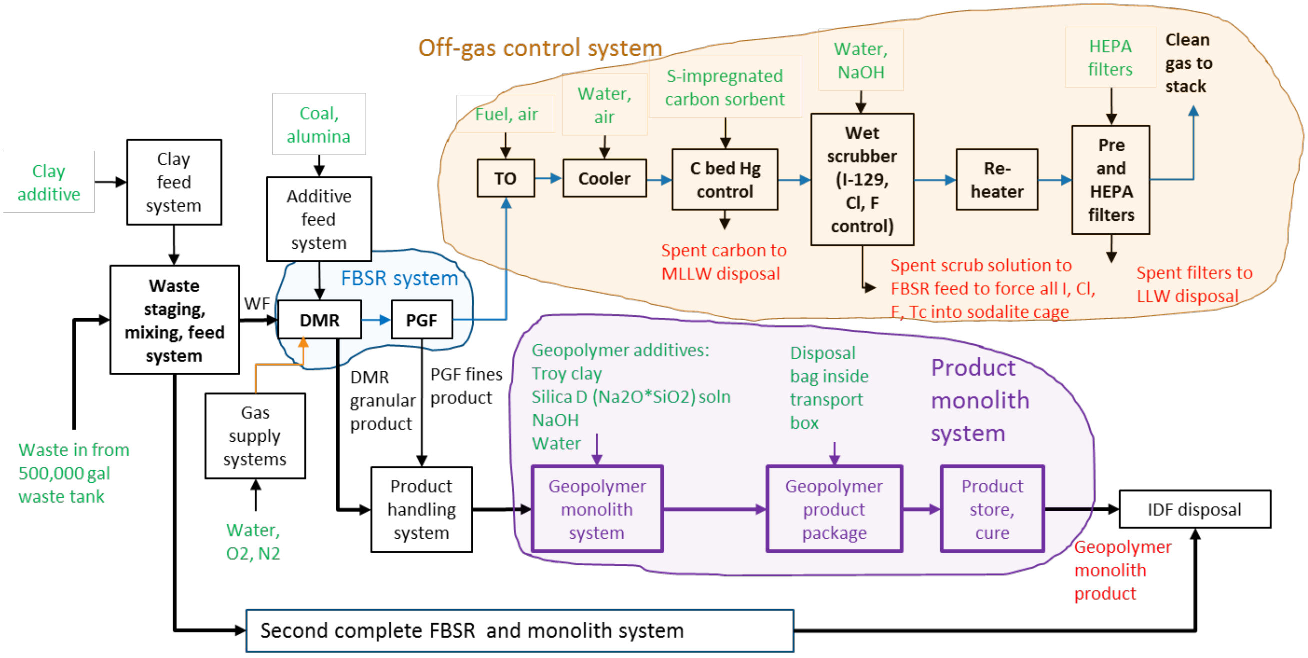


Figure D-2. Case 1 Mineralizing FBSR to IDF; solid monolith product disposed at IDF (secondary wastes also disposed at IDF)

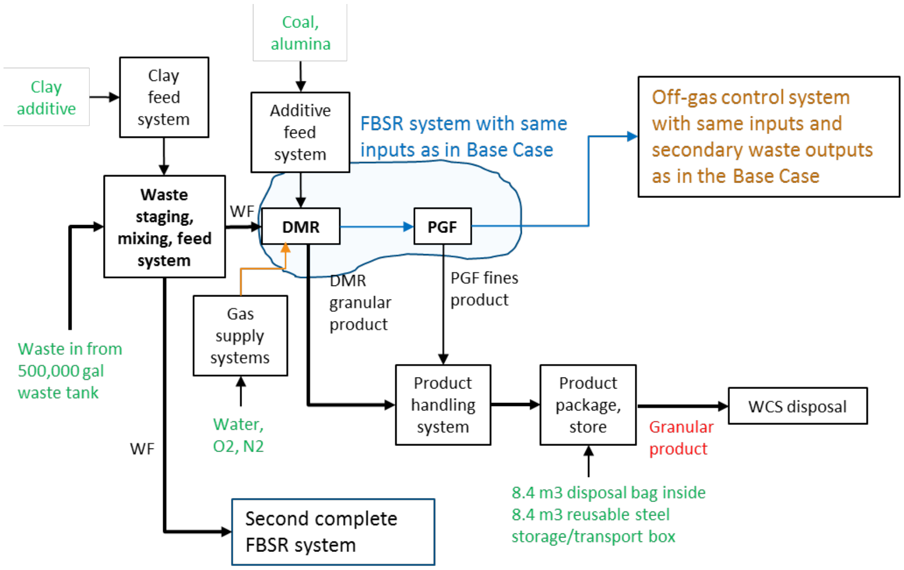


Figure D-3. Case 2, Mineralizing FBSR to WCS; granular solid product disposed at WCF (secondary wastes also disposed at WCF)

The highest WF rates occur in the first three years of SLAW treatment operations. After the first three years, the monthly feedrate varies by over 50x turndown ratio (ratio of the highest monthly WF rate to the lowest monthly WF rate). All FBSR options include the following features to accommodate this variation:

- Utilize the 500,000 gal waste holding tank upstream of the SLAW treatment system.
- Two 50,000 gal WF Hold tanks to provide time for sample analysis prior to mixing with mineralizing clay.
- Two 30,000 gal Mix/feed tanks for batch addition and mixing of clay/WF slurry.

- Two identical FBSR systems to maximize available capacity in first ~3 yrs.
- Shared waste staging, mixing, and feed system.

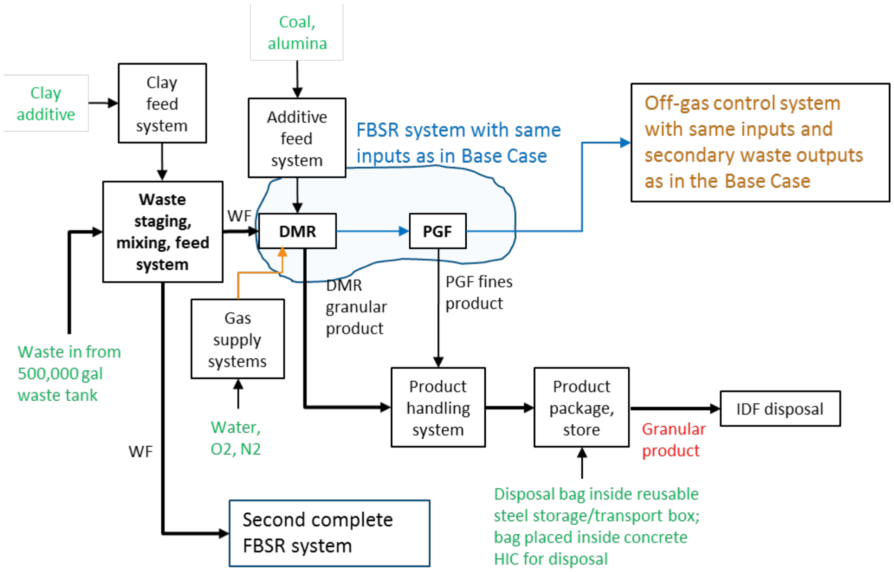


Figure D-4. Alternative Treatment Option 3c, Steam Reforming to WCS: Two DMR systems; granular solid product disposed at IDF inside concrete HICs (secondary wastes also disposed at IDF).

These figures show that the core DMR and PGF are only two of many components in the treatment system. While these boxes in the figures are not drawn to scale, the figures indicate that the core DMR and PGF represent only a fraction of the entire facility footprint.

D.3.1 FBSR Size and Processing Rates

The size and configuration of the DMR was estimated based on the range of monthly feed vector values after passing through the tank farm 500,000 gal tank, the WF Hold tanks, and the Mix/feed tanks; and assuming a 20% volume increase when clay is added. The nominal diameter of each DMR was set at 5 ft inside diameter, scaled based on the average monthly feed vector flowrate of 4.4 gpm (20% greater than the average feed vector flowrate of 3.6 gpm). This diameter is 25% larger than the IWTU diameter of 4 ft, based on scaling the cross section areas according to the volumetric feedrate (1.75 times greater than the 2.5 gpm IWTU feedrate).

The nominal vessel height dimensions were likewise scaled according to ratios for the IWTU:

- Bed height = 5 ft (approximately equal to the bed diameter).
- Bed section height = 8 ft (~25% more than the IWTU bed section height of 6.6 ft).
- Freeboard (including conical section) = 23 ft (assumed to be 100% higher than the IWTU freeboard + cone height of 11.6 ft, to allow for particle disengagement without the use of internal cyclones).

The nominal volume of the 5-ft diameter, 5-ft high fluidized bed is ~100 ft^3. With a fluidized density of about 0.7 g/cc (85% of the bulk product density of 0.8 g/cc), the nominal fluidized bed mass is about 4,000 lb.

D.3.2 FBSR Waste Feed System

Figure D-5 shows a concept design for the WF system. The actual configuration may change in a specific detailed design. Either one of two WF Hold tanks receives SLAW from a 500,000 gal waste tank used to stage tank farm waste (only one WF Hold Tank is shown in the figure for simplicity). Each WF Hold Tank can feed to either or both 30,000 gal Mix-feed tanks, and either Mix-feed Tank can feed to either or both DMRs. Each tank also is configured to recycle pumped feed back to the same tank, so that the feed systems from each tank remain flowing at all times to prevent solids deposition in the piping.

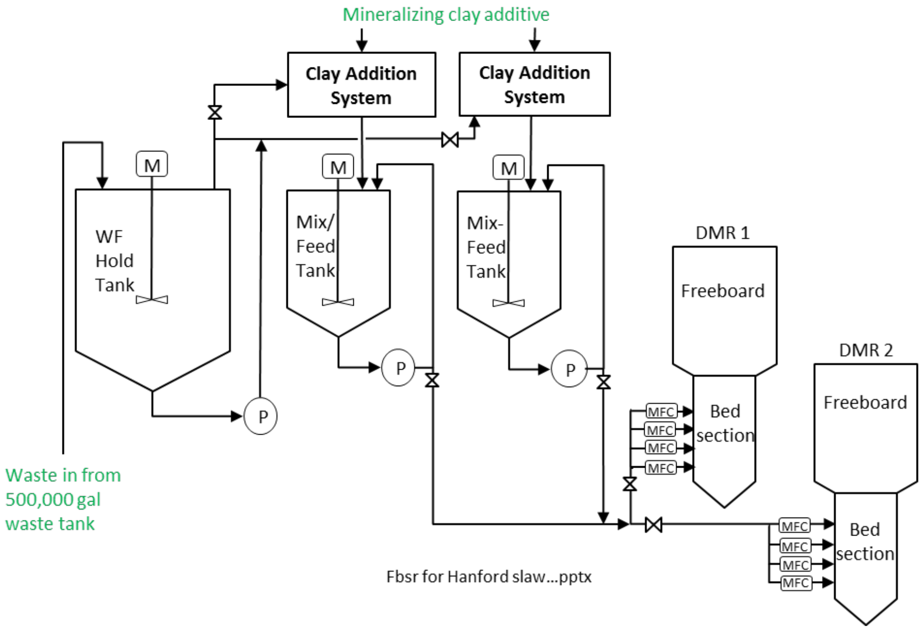


Figure D-5. Conceptual FBSR WF system

These tanks provide the needed feed tankage to (a) enable the two parallel FBSR systems, each with 70% availability on average, to process the maximum SLAW feedrate during the first three operating years, (b) provide 5-day turnaround time for batch sample analysis of the WF hold Tank contents before adding the clay, (c) provide 2 days for final feed blend sample analysis of each Mix-feed Tank, and (d) two days of feed time per Mix-feed Tank.

Commercially available clay is added in a Clay Addition System for each Mix-feed Tank (such as is shown in Figure D-6). Clay is metered from a hopper into an in-line mixer where it is mixed with WF metered from one of the WF Hold tanks. This premixes the clay into the WF as it enters either Mix-feed Tank. The correct amount of clay to add is determined for each WF Hold Tank batch based on batch analysis of that tank.

The WF can be fed to either or both of the two DMRs through between one and four feed nozzles that penetrate through the sides of each of the DMR vessels. The feed nozzles are oriented 90 degrees from each other around the circumference of the DMR. The flowrate to each feed nozzle is separately measured and controlled. Each feed nozzle is sized for an optimal WF rate of 1.3 gpm, approximately the same size as the IWTU feed nozzles, each sized for an optimal feedrate of 1.2 gpm. Water flushes (not shown in the figure) are used when feed nozzle flows are started and stopped to prevent clay sedimentation and drying in feed lines and feed nozzles.

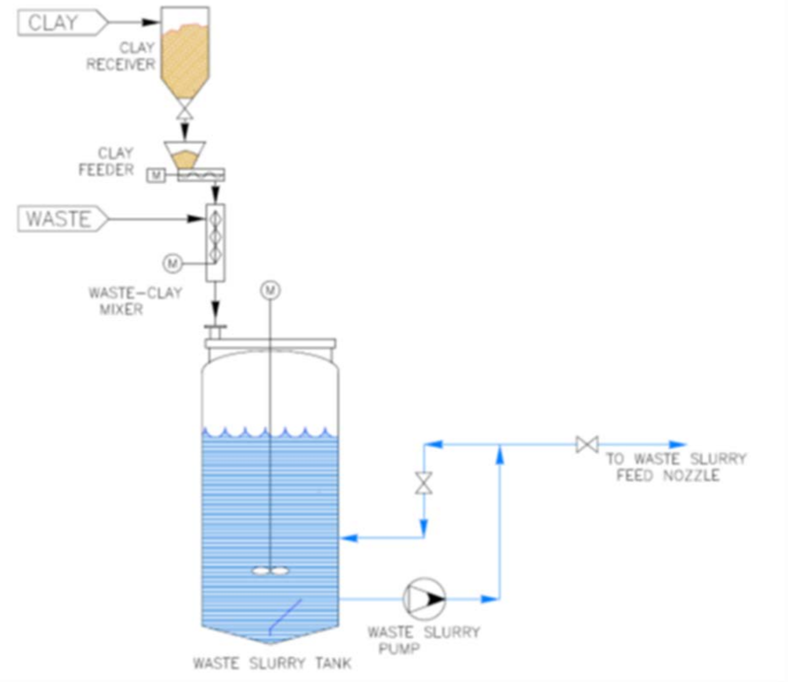


Figure D-6. Clay and waste high shear in-line mixing system concept design.

D.4 FBSR MASS AND ENERGY BALANCE

A mass and energy balance using HSC Chemistry with Excel inputs and outputs tracks all input streams to the FBSR process, and estimates energy requirements and the flowrates and compositions of the output process gas flowrate and mineral product streams. This model is currently used to track the performance and mass balance of the IWTU FBSR system. References for inputs to this model for the Hanford SLAW treatment process include the SLAW feed vector, the Advanced Remediation Technology pilot-scale Hanford LAW and Hanford WTP vitrification recycle stream mineralizing steam reforming test report (TTT 2009b), and the FBSR mineral wasteform downselect report (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015]).

The mass and energy balance includes 1,250 kg/hr of average feed vector (3.6 gpm), 620 kg/hr added clay, and 250 kg/hr added coal. Both the superheat of fluidizing steam (to 600°C) and heat losses (estimated at 65 KW from the DMR) are accounted for.

Most of the coal is oxidized and pyrolyzed through reactions with the added oxygen (210 kg/hr), WF nitrates, and steam. At steady state, the mass of coal in the fluidized bed is about 10% of the total bed mass; so when bed product is removed either from the bottom of the DMR, or by elutriation from the DMR into the PGF, about 20% of the input coal remains partially unreacted (coal char) and comingled with the mineralized product. The mineralized product is expected to contain about 5 wt% incompletely reacted coal particles.

About 80% of the input coal is reacted to CO_2, H_2O, H_2, CO, gasified hydrocarbons, mainly CH_4, and SO_x. Most (about 90%) of the reacted coal is converted to CO_2 and H_2O; about 10% is converted to H_2, CO, and gasified hydrocarbons to produce reducing stoichiometry to destroy the nitrates, nitrites, NO_x, and WF hydrocarbons.

The coal used for the IWTU was specified to be a unique low-S, low-ash, low-moisture, low-volatiles precalcined coal procured overseas because this precalcined coal is not presently produced in the U.S. Other coals including un-calcined coal from various sources have also been tested successfully. A domestic bituminous coal from Penn

Keystone Coal Company has recently been specified by Studsvik for fluidized bed steam reforming. This eliminates concerns about the long term availability of non-U.S. coals.

Ash from the reacted coal is also incorporated into the mineralized product. With a maximum of 10 wt% ash in the input coal, the coal ash represents up to about 25 kg/hr, less than 2.7 wt% of the mineralized product. The total mineralized product volume increase from the coal/char and coal ash is about 10%.

Figure D-7 summarizes the mass balance in terms of 1 liter of the average feed vector.

- 660 g clay is added per L to produce the mineralized product
- 260 g coal is burned per L
- 1.0 kg (1.2 L, at a bulk density of about 0.8 g/cc) of granular product is produced, including incompletely reacted coal and coal ash.
- 1.89 kg (1.0 L at a density of 1.8 g/cc) geopolymer product. The volume of the monolith product is actually equal to or less than the volume of the granular product because of the differences in densities.
- Amounts of secondary wastes and I-129 and Tc-99 partitioning data are provided for spent carbon (used for Hg emissions control), spent HEPA filters, and used equipment decontamination solution. Decon solution, spent equipment, and job control wastes like used personal protective equipment, are not included in this analysis because they are expected to contain very low or non-detectable levels of radionuclides like I-129 and Tc-99 and so are not discriminators in the evaluation of SLAW treatment technologies.

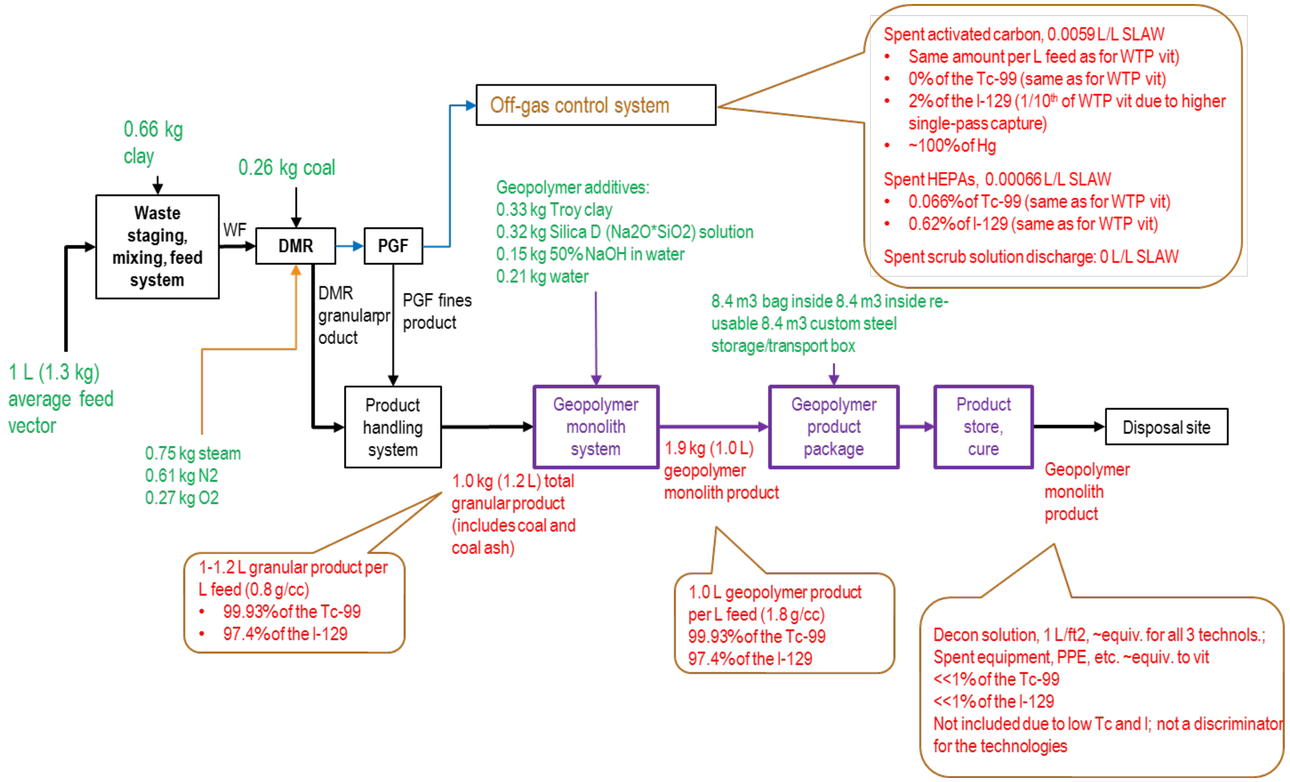


Figure D-7 Initial mass balance results for FBSR treatment of Hanford SLAW.

D.5 PROCESS SAFETY

As a thermochemical process, steam reforming has various risks normally associated with thermal processes. These include worker exposures to heat, chemical, radiation, radioactive contamination, and ergonomic hazards, and noncompliant air emissions. These risks are mitigated by methods established and proven in nuclear and other industries as shown in Tables D-2 and D-3. Engineered controls such as containment of the process inside sealed systems, use of thermal insulation, and use of offgas control systems. Safety of workers and the public is to be expected for the steam reforming process, and has been demonstrated in pilot-scale, engineering scale, and full scale steam reforming operations within the DOE system.

The use of engineered controls is augmented with administrative controls. One of the most important administrative controls is the use of operating procedures and operating limits for temperatures, flowrates, and pressures, that ensure that all process conditions are maintained within parameters established to be safe and that produce the desired wasteform.

The use of personal protective equipment (PPE) is also a necessary and standard practice to augment engineered and administrative controls.

Table D-2. Worker exposure risks and mitigations.

Risks	**Mitigations in addition to procedures and PPE**
Heat	Insulation, process containment
Chemicals	Process containment
Radiation, radioactive contamination	Process containment
Ergonomic	Engineering, tools

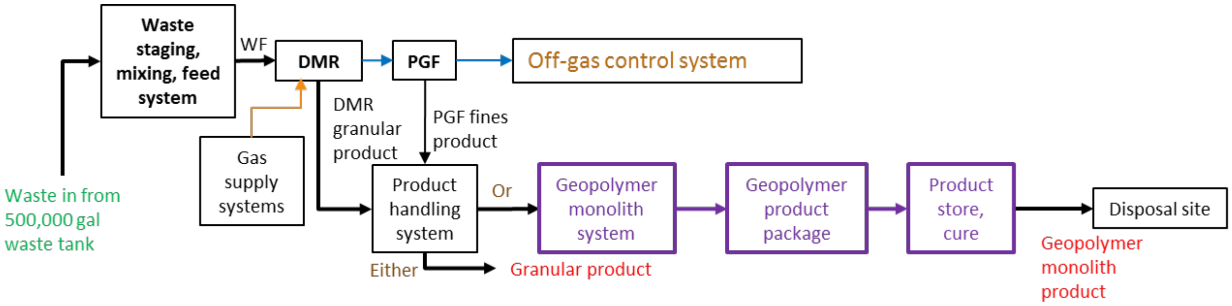
Table D-3. Air emissions compliance.

Emissions	**Mitigations in addition to containment & operating limits**
Radionuclides	Multiple redundant filters and scrubbing, HEPAs
NOx and Hazardous/toxic organics	Steam reforming chemistry, kinetics, mass & heat transfer
Hazardous/toxic particulate, metals	Multiple redundant filters and scrubbing, HEPAs
Hazardous/toxic acid gases	Multiple dry and wet scrubbing

D.6 CONFIDENCE THAT THE FBSR PROCESS WILL WORK – TECHNOLOGY READINESS LEVEL

No formal TRL evaluation has been done for mineralizing FBSR for treating Hanford SLAW. The TRL estimates shown in Figure D-8 for different facility subsystems result from informal and subjective evaluations of this team. Care should be taken as to how the TRL approach is used. DOE 2013 cautions against using TRLs as a sole means of comparing technologies, and cautions against using TRLs as a means of comparison without also estimating in a Technology Maturation Plan (TMP) what it would take to advance the maturity of competing technologies.

Many portions of the steam reforming concept facility such as the WF system, the gas and additive supply and feed systems, most of the off-gas system, and solid product storage, transport, and disposal systems include commercial, mature technologies for full-scale use in various mature industries. These portions of the facility contain mature technologies are already demonstrated in the Erwin Resin*Solutions* Facility and in the IWTU. These are generally rated at high TRL.



Estimated Technology Readiness Level, assumptions

- Feed systems TRL Hi

(Not unique to FBSR, common commercial equipment)

- DMR TRL Med
- Product system TRL Med
- (Unique to FBSR, requires special equipment)

- Monolith system TRL Med

(Not unique to FBSR, common commercial equipment)

- Off-gas system TRL Hi
- Wet scrubber TRL Med

(Not unique to FBSR, common commercial equipment)

- Product cure, store, transport TRL Med-Hi

(Not unique to FBSR, common commercial equipment)

- Integrated FBSR system TRL is Medium-high because of its dependence on multiple integrated subsystems

(TRL 1-3 = Low; 4-6 = Med; 7-9 = Hi)

Figure D-8 Rough maturity level estimates for the FBSR processing system.

The core DMR, PGF, granular product handling systems, and possibly a wet scrubber for capture and recycle of trace levels of halogens and radionuclides are rated at a medium TRL for this particular use for treating Hanford SLAW. While the Erwin Resin*Solutions* Facility has operated at full scale for many years, the low-level waste (LLW) it processes (primarily spent ion exchange resins from U.S. commercial nuclear power plants) is quite different from the Hanford SLAW. While its full scale operation uses equipment and subsystems that can translate to a Hanford SLAW treatment facility, some of these applications are indirect and in many cases not yet fully demonstrated for this application at full scale. And while the Erwin Resin*Solutions* Facility also adds clay to produce a mineralized product, the significant difference in primary WFs makes the clay addition methodology much different than in the Hanford SLAW concept.

Likewise, some of the IWTU design and operation is even more similar to a Hanford SLAW treatment process, but some subsystems have not yet been proven beyond a pilot-scale level. Indeed, the non-radioactive startup process for the IWTU, which started in 2012, has now gone several years beyond is initially planned duration, and is not yet complete – mainly because equipment and subsystems that were proven in the full-scale Studsvik Processing Facility or in pilot-scale Engineering Scale Test Demonstration (ESTD) tests still have required trouble-shooting and modifications to make them function as designed at full scale in the IWTU.

Many system and subsystem issues with the IWTU have now been solved; startup/commissioning may soon be complete. When complete, this experience will increase the technical maturity of key FBSR components. But some of the design and function of a Hanford SLAW treatment process would by necessity need to be different from the Erwin Resin*Solutions* Facility and the IWTU because of the goal to produce the durable mineral wasteform for the Hanford SLAW, versus the carbonate-based product to be produced at the IWTU. For example, the DMR may need to be refractory-lined, significantly different from the IWTU DMR. The higher operating temperatures may also cause changes to the PGF and other downstream subsystems.

The IWTU has been described as “first-of-a-kind” system. Equipment, subsystems, and applications for a Hanford SLAW steam reforming facility that could still be considered first-of-a-kind, at least as applied to treating Hanford SLAW for permanent disposal, include:

- Mineralizing clay addition process
- DMR that produces a durable mineralized product
- Product handling system
- Geopolymer monolithing system
- Integration of these systems with other subsystems not considered first-of-a-kind into a complete system.

Maturing some components to a high TRL will still require some technology maturation work. The estimated costs and schedule to mature all parts of a Hanford SLAW treatment process are included in the total FBSR costs and schedule for treating SLAW.

D.7 COST AND SCHEDULE

The IWTU and the Erwin Resin*Solutions* Facility are the most similar, full-scale, radioactive steam reforming processes to the Hanford SLAW FBSR concept design. Capital and operating costs for these two facilities are candidates to use as a benchmark for estimating costs for the Hanford SLAW FBSR concept. However, the Resin*Solutions* Facility is sufficiently different by design and use, including its design and operation as a commercial facility rather than a DOE facility, that it is considered by the team to be less representative of the Hanford SLAW FBSR concept. So only the costs for the IWTU were used as a benchmark for the Hanford SLAW FBSR concept. The IWTU costs were adjusted to reduce costs associated with the IWTU hot cells that are not needed for SLAW treatment, and to increase costs due to the use of two 25% larger diameter DMR systems and associated equipment.

The costs for the Hanford SLAW FBSR concept are shown in Tables D-4 and D-5. More detail of these costs are provided in the cost estimating sections of this report. The technology development and pilot plant costs are those estimated costs associated with the technology maturation needed to mature the components of, and the integrated, FBSR system as applicable to SLAW treatment. The OPEX/Life Cycle costs are also impacted by current technical maturity. The IDF expansion costs are estimated be small compared to the other cost factors. The shipment to WCS costs only apply to Case 2, where they are not the dominant costs, but are about 15-20% of the total costs.

A range of 10-15 years was estimated for the time needed to progress through technology development, pilot plant testing, plant design, construction, startup, and readiness for hot startup. The time duration for the IWTU from pilot-scale testing at Hazen (2005) to now (2019) is 14 years, although seven of those years has occurred after the IWTU was constructed and started up. The technology maturation plan assumed in this study provides more time and funding for technology development and pilot plant operations to enable less time and cost for testing and modifications after plant construction. The technology maturation plan and full-scale design is expected to benefit greatly from the IWTU experience – but that potential benefit is not assumed in the current cost and schedule estimates.

Table D-4 Estimated costs ($M) for FBSR Case 1

FBSR Case 1	Low End	Analog Estimate*	High End	Comments
Technology Development	480	------------------------	1080	Set at 25% of TPC
Pilot Operations	1080	1800	2500	See Note 2.
Total Project Cost (TPC)	1930	2150	4300	(-10% / +100%)
Operations (OPEX)	2520	3150	3780	(-20% / +20%)
Major Equipment	290	-----------------------	650	Set at 15% of TPC (Note 3)
Total Program Cost	6300		12330	

*The analog selected for steam reforming was INL Integrated Waste Treatment Unit. See Appendix H, "Cost Estimate Methodology and Results."

FBSR costs note 1: Values are rounded.

FBSR costs note 2: Cost is estimated for integrated WTP (with SLAW) pilot to optimize operations with process rates and system outage/downtime.

FBRS costs note 3: Based on SME input and IWTU development / startup.

Table D-5 Estimated costs ($M) for FBSR Case 2

FBSR Case 2	Low End	Analog Estimate	High End	Notes
Technology Development	480	----------------------	1080	Held Constant w/ FBSR Case 1
Pilot Operations	1000	1800	2600	
Total Project Cost (TPC)	2310	2570	5140	(-10% / +100%)
Operations (OPEX)	3270	3920	4900	(-20% / +20%)
Major Equipment	330	-----------------------	740	Set at 15% of TPC
Off-Site Trans/Disposal	1850	-----------------------	2780	SME Quote / 150% Quote
Total Program Cost	9240		17,240	

*The analog selected for steam reforming was INL Integrated Waste Treatment Unit. See Appendix H, "Cost Estimate Methodology and Results."

A schedule that could provide time for technology maturation and to design, construct, and start up a Hanford SLAW FBSR facility in time to be available according to the schedule of the feed vector is:

- 2019: Address DOE and stakeholder concerns
- 2021: Initiate bench and pilot-scale demonstration of key components and the integrated system.
- 2026: Complete integrated pilot plant demonstration testing using simulated and radioactive waste, and full-scale non-radioactive demonstration. Start plant design and construction phase. Start permitting.
- 2031: Complete plant design and construction. Commence startup and transition operations.
- 2033: Complete plant transition from startup to rad operations. Complete permitting. Commence radioactive operations.

D.8 REGULATORY COMPLIANCE

The steam reforming process can be operated in full compliance with applicable regulations. This has been demonstrated in general with the IWTU and with the Erwin Resin*Solutions* facility. One of the conclusions of the 2012 Hanford tank closure and waste management environmental impact statement (TC and WM EIS, DOE

2012) was that "…The steam reformed wasteform would not be equal to that of the WTP glass…" This and other conclusions about non-glass wasteforms and steam reformed wasteforms was based on data available at that time. Other documents contemporaneous to the 2012 EIS drew different conclusions. The National Research Council "Wasteforms Technology and Performance, Final Report," (NRC 2011) concludes "…crystalline ceramic wasteforms produced by fluidized bed steam reforming have good radionuclide retention properties and waste loadings comparable to, or greater than, borosilicate glass. This wasteform material is also potentially useful for immobilizing LAW."

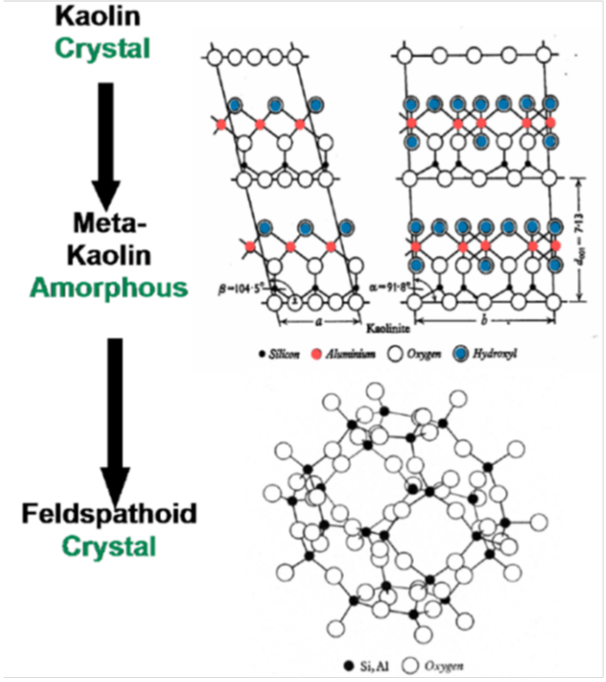
Since both the 2011 National Research Council report (NRC 2011) and the 2012 TC and WM EIS, the mineral wasteform produced from the mineralizing FBSR process was studied more extensively between 2012-2015. Results of these studies are reported in many individual documents, and summarized in the 2015 downselect report (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015]). Much of the following description and performance of the FBSR mineral wasteform and is extracted from the downselect report.

Based on results of the 2012-2015 studies, it seems that some conclusions of the 2012 TC and WM EIS might need to be re-evaluated. These most recent results indicate that the steam reforming process has a high likelihood to meet DOE technical performance criteria for onsite disposal (IDF) (e.g., DOE Order 435.1) and for offsite transport and disposal at WCS (TX).

D.8.1 The Mineralizing Process

The mineralizing process begins with the kaolin clay ($Al_2Si_2O_5(OH)_4$) added to the WF. The clay particles dehydrate as the OH is lost when heated above 550°C in the DMR (Figure D-9). This causes the aluminum atoms to become charge-imbalanced and the clay becomes amorphous (loses its crystalline structure) and very reactive. This amorphous clay (meta-kaolin) can further evolve to feldspathoids. Being charge-imbalanced, the metakaolin also readily reacts with cations in the salt waste such as Na to form nepheline ($NaAlSiO_4$ with hexagonal symmetry) and carnegieite (nominally $NaAlSiO_4$ with orthorhombic symmetry). Nepheline can further react with the waste to form sodalite(s) where the Na is exchanged with other cations such as Cs or K. The resulting minerals and approximate concentrations for SLAW composition ranges include:

- Nepheline (nominally hexagonal $NaAlSiO_4$) and carnegieite (nominally orthorhombic $NaAlSiO_4$), estimated to be about 60-80 wt% of the total mineral product SLAW compositions.
- Sodalite (nominally $M_8(Al_6Si_6O_{24})X_2$, where M is an alkali cation such as Cs, K, Na, etc. and X is a monovalent anion or a monovalent or divalent oxyanion, such as Br-, Cl-, I-, TcO_4-, ReO_4-, SO_4-2, etc.). Estimated to be up to 5-10 wt% of the total mineral product, depending on how much of these anion species are present in the SLAW compositions, and how much of the radionuclides are incorporated into sodalite cages vs the mineral structure.
- Nosean (nominally $Na_8[AlSiO_4]_6SO_4$ with a larger cubic sodalite structure), estimated to be on the order of 6-12 wt% of the total mineral product, depending on the concentration of S in the SLAW compositions.
- Silica (SiO_2) and alumina (Al_2O_3), estimated to be on the order of 1-10 wt% of the total mineral product.



Resultant Nepheline – Kalsilite structures that can contain radionuclides:
$Na_xAl_ySi_zO_4$
$CsAlSiO_4$
$RbAlSiO_4$
$(Ca_{0.5},Sr_{0.5})AlSiO_4$
$(Sr,Ba)Al_2O_4$
$(Na,Ca_{0.5})YSiO_4$
$(Na,K)LaSiO_4$
$(Na,K,Ca_{0.5})NdSiO_4$

Group 1, 2, and certain other elements

Anions that can be incorporated into cages:		
Anion	Mineral Name	Oxidation State
F^-	F-sodalite	-1
Cl-	Cl-sodalite	-1
ClO_4^-	Cl-sodalite	-1
SO_4^{2-}	Nosean	+6
TcO_4^-	Tc-sodalite	+7
ReO_4^-	Re-sodalite	+7
I^-	I-sodalite	-1
Br^-	Br-sodalite	-1

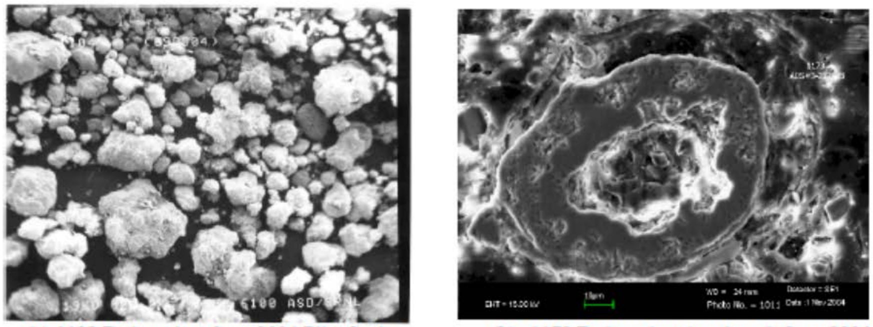
Figure D-9 Conversion of kaolin clay to reactive, amorphous meta-kaolin and to feldspathoid crystals during steam reforming (from Grimm 1953 and SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015]).

These nepheline, sodalite, nosean, and carnegieite structures incorporate elements in the WF either into the mineral structure (nepheline/carnegeite) or inside "cages" (sodalites/nosean) of suitable sizes that can contain the halogens and anionic radionuclides species. These are the same types of mineral phases that have been developed as target mineral phases for not only FBSR mineral products but also high level waste (HLW) ceramic and glass bonded sodalite wasteforms. The relatively small amounts of the sodalite and nosean minerals compared to the larger amounts of nepheline/carnegieite minerals in the model result from the relatively small amounts of anions and radionuclides (ranging from about 3-14 mole% of the Na) and the sulfur (ranging from about 0.4-1 mole%) in the SLAW feed vector.

D.8.2 Granular and Monolith Mineral Wasteforms

Figure D-10 shows scanning electron micrographs of the granular mineralized wasteform. The individual particles from the fluidized bed range in size from under 10 microns to about 1 mm. Larger particles, especially of incompletely oxidized coal up to about 1 cm (not shown in the figure), are also typically present and can be up to about 5 wt% of the total product mass. The granular solid mineralized product requires solids handling systems including dense and dilute-phase pneumatic transport, product filtration and collection systems, and control of fine particles.

Figure D-11 shows a photograph of a monolith of FBSR mineral product formed with additives into a geopolymer monolith, such as would be produced in Treatment Option 3, the Steam Reforming Base Case.



(a) 1123 Bed product from 2004 Pilot Scale Testing

(b) 1173 Bed product (sectioned) from 2004 Pilot Scale Testing

Figure D-10 Scanning electron micrographs of bed product from INL SBW; Science Applications International Corporation Science and Technology Applications Research (SAIC-STAR) 6 in. diameter FBSR (Jantzen 2015).

Figure D-11 Troy clay geopolymer monolith of Hanford LAW 60% FBSR product (Jantzen 2015).

D.8.3 Wasteform Mineralogy Control

The “MINCALC” process control strategy was developed at SRNL for determining best mix and amount of clay additive to use in the steam reforming process to produce the desired mineralized product. The amount and type of clay is determined based on the input LAW composition so that the combined mixture achieves the target Na_2O – Al_2O_3 – SiO_2 composition. This is done for every WF batch.

The downselect program studied monolith production using both fly ash and clay additives and sodium silicate, added to the granular mineralized product to produce a geopolymer monolith with the desired overall Na_2O – Al_2O_3 – SiO_2 stoichiometry similar to the target stoichiometry for the monoliths.

D.8.4 Product Analyses and Durability Tests

With respect to wasteforms and wasteform tests, NRC 2011 findings include:

- “Two essential characteristics of wasteforms govern their performance in disposal systems: (1) capacity for immobilizing radioactive or hazardous constituents, and (2) durability.”
- “Wasteform tests are used for three purposes: (1) to ensure wasteform product consistency; (2) to elucidate wasteform release mechanisms; and (3) to measure wasteform release rates.

In accordance with the recommendations from NRC 2011, the following durability tests were used for both the granular and monolith wasteforms in the SRNL-ORNL-PNNL-WRPS downselect:

- ASTM C1285 Product Consistency Test (PCT) (short and long-term).
- ANSI 16.1/ASTM C1308 Accelerated Leach Test.
- EPA Toxicity Characteristic Leaching Procedure (TCLP).
- ASTM C1662 Single-Pass Flow-Through Test (SPFT) on product of Rassat 67 tank blend LAW (Rassat 2002).
- Pressure Unsaturated Flow-through (PUF) test on product of Rassat 67 tank blend LAW.

These tests demonstrate that the mineralized wasteform could likely meet requirements of the IDF (Burbank 2002, Qafoku 2011, and NRC 1991), the Hanford WTP contract (DOE/ORP 2000), and DOE Order 435.1.

Table D-6 summarizes the performance tests by many different researchers at PNNL, ORNL, SRNL, and WRPS to demonstrate if the mineralized wasteform can meet these requirements. Results have been reported in dozens of reports and other publications, and summarized in the SRNL-ORNL-PNNL-WRPS downselect report. These tests were performed on the wasteforms produced by steam reforming simulated and actual Hanford LAW, Hanford WTP secondary waste (SW), Savannah River Site (SRS) LAW shimmed (modified) to simulate the

Hanford LAW (Rassat) blend, and simulated INL SBW. Samples were selected for analysis from bench and pilot-scale tests with actual radioactive waste and non-radioactive simulants, using a "tie-back" strategy to (a) demonstrate the similarity of the radioactive mineral products to the mineral products of the non-radioactive tests, so that (b) the durability test results from both the radioactive and non-radioactive tests could be used to allow determination of the suitability of the FBSR wasteform for disposal at Hanford in the IDF.

X-ray Absorption Spectroscopy (XAS) indicated that the distribution of Re (the Tc surrogate) in non-radioactive surrogate testing is in the +7 state in sodalite cage; which has low solubility in durability testing. XAS analysis of mineral products from actual radioactive tests show that 56-79% of Tc-99 is in the +7 state in sodalite cages; the remainder is in a +4 state in TcO_2 or $Tc_2S(S_3)_2$; with equally low solubility during durability testing. TcO_2 is the same oxide species present in HLW waste glasses formed under slightly reducing flowsheets like the Defense Waste Processing Facility (DWPF).

Results of these performance tests are reported in detail in Jantzen 2015 and summarized below.

PCT Results

- No impact of product reducing–oxidizing ratio (REDOX) on durability in short and long-term PCT tests (except for Cr in TCLP, which can be controlled by adding some iron oxide to tie up the Cr in $FeCr_2O_4$).
- <2 g/m^2 leachable per PCT for granular and monolith (using geometric surface area, equivalent to glass WF).
- <2 orders of magnitude lower than 2 g/m^2 using Brunauer–Emmett–Teller (BET) surface area.
- Durability results for the non-radioactive constituents from the 2-in. SRNL BSR testing and the 15-in. pilot plant agree with the previous data from 2001 and 2004 6-in. pilot plant tests.
- Long-term PCT testing (1, 3, 6, and 12 month) at 90°C by ASTM C1285: no significant based on XRD.

SPFT Results

- Relatively low forward dissolution rate ~10^{-3} $g/(m^2d)$.
- Re release was similar to both I and Tc release in this wasteform.
- Re, I, Tc, and S all showed delayed release from the sodalite phase(s) confirming that the Si-O-Al bonds of the sodalite cage have to dissolve before these species can be released.
- Si release from the SRNL Bench Scale Reformer (BSR) Rassat product was two orders of magnitude lower than for LAWA44 glass.

PUF Test Results

The PUF test simulates accelerated weathering of materials under hydraulically unsaturated conditions, thus mimicking the open-flow and transport properties that most likely will be present at the Hanford IDF. Results of several studies are summarized below (McGrail 2003b, Neeway 2014, Pierce 2007, Pierce 2012, Pierce 2014):

- PUF tests 1-year long were performed on LAW FBSR granular products from the BSR and in 15-in. pilot tests.
- Na, Si, Al, and Cs release decreased as a function of time.
- Iodine and Re release was steady.
- Differences in the release rates of Na, Si, Al and Cs compared to I and Re suggest that I and Re release from the sodalite cage occurs at different rates compared with the dissolution of the dominant nepheline phase.
- The 2.5-year-long PUF test results for 2004 6-in. pilot scale FBSR products were similar to results of the 1-yr BSR and 15-in. pilot plant product PUF test results.
- Elemental release rates and geochemical modeling suggest that Al and Na release was controlled by nepheline solubility, whereas Si release was controlled by amorphous silica solubility after being released from the Na_2O-Al_2O_3-SiO_2 (NAS) matrix.
- Similar Re and S releases suggests that their release is either from the same phase or from different phases with similar stability.

- Re release was about 10x lower than Tc release [$(2.1 \pm 0.3) \times 10^{-2}$ g/(m^2d)] from LAW AN102 glass.

Results of tests performed on mineralized product monoliths are summarized below:

- ASTM308/ANSI 16.1 test duration was up to 90 days. For the Hanford IDF, the solidified waste is considered effectively treated for IDF disposal if the leach index (LI) for Re and Tc ≥ 9 after a few days and the LI for Na ≥ 6 in 2 hours.
- FBSR monoliths pass ANSI/ANS 16.1/ASTM C1308 durability testing with LI(Re) ≥9 in 5 days and achieving the LI(Na) in the first few hours.
- Clay monoliths had better durability than did fly ash durability.
- ASTM308/ANSI 16.1 and PCT tests (with leach rates <2 g/m^2) indicated that the binder material did not degrade the granular product durability.
- SPFT and PCT demonstrated slower releases from the monoliths than from the granular product but PUF release rates for the monoliths were faster than for the granular product.
- ASTM C39 Compressive Strength tests showed that the monoliths passed compression testing at >500 psi but clay based monoliths performed better than fly ash based geopolymers.

Table D-6 Summary of FBSR mineralized wasteform studies (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015]).

Pilot Scale Facility, date	Waste	Granular PfCT Testing	TCLP of Granular Form	Granular SPFT Testing	Preliminary Risk Assessment	Product Tested	Monolith	Monolith PCT Testing	Monolith SPFT Testing	Monolith ANS 16.1/ ASTM C1308 Testing	TCLP of Monolith
Non-Radioactive Testing											
HRI/TTT 12/2001 Jantzen 2002	LAW Env. C AN-107	Jantzen 2004	Jantzen 2002, 2004	McGrail 2003a, 2003b; PUF testing, Pierce 2007	Mann 2003	Bed	No	N/A			
		Pariezs 2005, Jantzen 2006a, 2006b		None	Jantzen 2013	Fines					
SAIC/STAR 7/03 Soelberg 2004a, Marshall 2003	SBW			None	None	Bed	Yes (samples were combined; 20% LAW, 32 % SBW and 45% startup bed)	Jantzen 2006c, 2007b	N/A		
SAIC/STAR 8/04 Olson 2004a	LAW Rassat			Jantzen 2006b, 2007; Lorier 2005; and PUF, Pierce 2012, 2014	Jantzen 2006b, 2007a, 2013; Lorier 2005	Bed and fines Separate					
SAIC/STAR 7/04 & 11/04 Olson 2004b	SBW			Lorier 2005, Jantzen 2006b	None						
HRI/TTT 12/06	SBW	Crawford 2007		None	None		No	N/A			
HRI/TTT 2008 THOR 2009b	LAW Rassat	Jantzen 2010, 2011, 2013; Crawford 2011, Evans 2012	Crawford 2011, Jantzen 2011, Evans 2012	Neeway 2012	Jantzen 2013	Bed and fines together	Yes	Crawford 2011	PNNL	Jantzen 2013	
	WTP-SW			None	None				None	Crawford 2014, Pires 2011	Crawford 2011, Jantzen 2011, Evans 2012
Radioactive Testing											
SRNL/BSR 2010-2013	LAW Rassat	Jantzen 2012, 2013		Neeway 2012, 2013, 2014, Williams 2015	Jantzen 2013	Bed, fines together	Yes	Jantzen 2013	Neeway 2013	Jantzen 2013	
	WTP-SW	Crawford 2014, Jantzen 2012		None	None			Crawford 2014	None	Crawford 2014	

PCT, SPFT, and ANSI/ANS16.1/ASTM C1308/EPA 131 monolith immersion tests all similar with different leachate replenishment intervals.
PUF tests were done on LAW Env. – low activity waste envelope A, B, and C. Compressive strength tests were also performed on monolith samples, but not indicated in this table.

D.8.5 Air Emissions Compliance and Retention of Radionuclides and Hazardous Metals

FBSR is expected to meet emission requirements similar to WTP LAW vitrification as shown in Table D-7. The combination of pyrolysis in the DMR and efficient oxidation in the thermal oxidizer destroys nitrates, nitrites, and organic compounds in the SLAW feed vector. Testing has demonstrated compliance to the stringent HWC MACT standards for CO, total hydrocarbon, and dioxin emissions, and Principal Organic Hazardous Constituent (POHC) destruction. This pyrolysis/oxidation combination can also destroy ammonia compounds that could be in liquid secondary wastes from WTP vitrification and in the SLAW feed vector. Since the FBSR process does not require NO_x selective catalytic reduction (SCR), no ammonia is fed into the off-gas system, and no "ammonia slip" occurs that can be problematic if the SCR operation becomes less controlled or is subject to variations in the incoming NO_x concentrations.

Single-pass FBSR control efficiencies have been measured in pilot and bench-scale tests for elements that could be in the SLAW WF. Certain key elements identified in the SLAW feed vector present challenges. Examples of how some of these challenges are addressed in FBSR are summarized below.

Mercury is not captured in FBSR product, but evolves into the process gas stream, like it does in other thermal processes. None is expected to be captured in the FBSR solid wasteform. Instead, as is already demonstrated in pilot and engineering scale steam reforming tests, and designed and installed in the INL IWTU steam reforming process, it would be captured in a fixed bed of S-impregnated activated carbon in the off-gas system.

Table D-7 Expected FBSR off-gas control performance requirements.

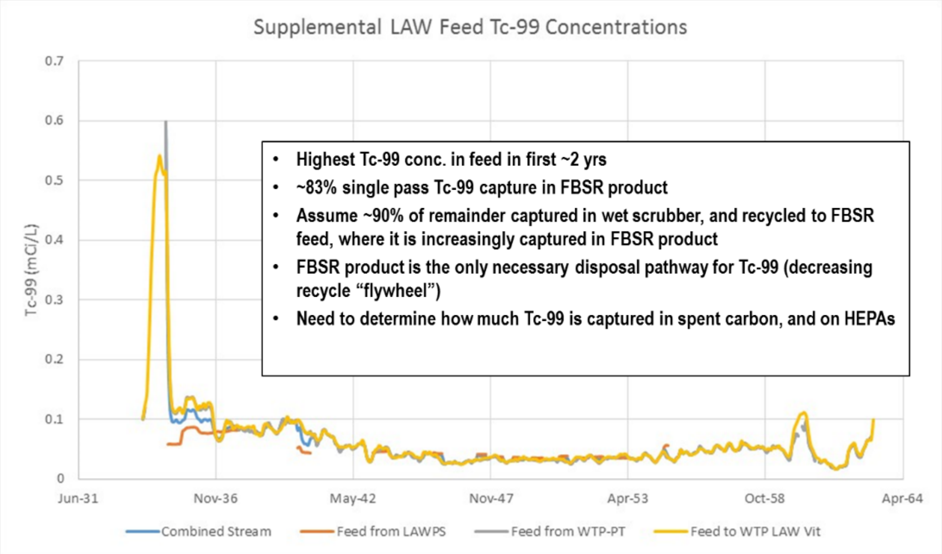
Parameter	Requirement or expected value	Basis
Stack gas NO_x concentration	≤500 ppmv dry	Pilot plant tests indicate this level is achievable; and it is assumed that this level of NO_x emissions is regulatorily acceptable.
WF organics destruction efficiency	≥99.99%	Assume bounding requirement is HWC MACT standards for principal organic hazardous constituents
Hg decontamination factor (DF)	≥450	Assume FBSR requirement is similar to WTP LAW vitrification requirements. 100% of the Hg evolves to the off-gas where it is controlled using sulfur-impregnated activated carbon. Test data shows that Tc-99 and I-129, halogens Cl, F, I, and S are captured to a large degree in a single pass in the FBSR solid wasteform. The total required control efficiency is achieved by additional >90-95% capture of these elements in the wet scrubber, and recycling them back to the FBSR.
HCl capture efficiency	≥97%	
HF capture efficiency	≥97%	
I-129 capture efficiency	≥99%	
Particulate capture efficiency	≥99.95%	For final bank of HEPA filters when tested in-situ.
Combined total particulate DF	2E+11	Estimated minimum combined performance for process gas filter (100); followed by at least one wet scrubber, prefilter, and two HEPA filters in series (2E+9, from Jubin 2012).

Notes:
1. SO_2 emissions, while not regulated under the HWC MACT standards, are expected to be captured in the product and >90% captured in the wet scrubber (Jubin 2012).

2. Additional requirements may apply, such as for other radionuclides, low volatile metals (As, Be, and Cr) or semivolatile metals (Cd and Pb), to the extent those are present in the WF. Semivolatile or low volatile elements are expected to be adequately captured with a combined particulate DF of 2E+9 (Jubin 2012).

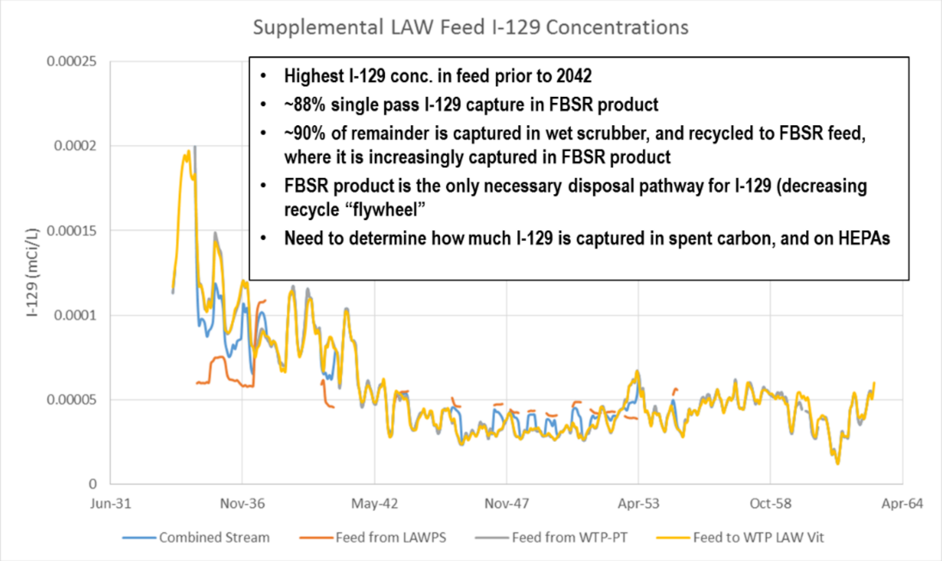
As Figure D-12 shows, the FBSR product is the only necessary disposal path for Tc-99; but some may also be captured in spent carbon (for Hg control), in the wet scrubber, and in spent HEPA filters. Tc-99 that is captured in the wet scrubber is recycled back the DMR, where most of it is captured in the FBSR product. With the high single pass capture efficiency of about 83-86% in the FBSR product (based on Tc measurements [Jantzen 2014] and Re measurements as a surrogate for Tc [THOR Treatment Technologies 2009b]), significantly decreasing amounts of volatilized Tc-99 remain in the recycle “flywheel.” The concentration of the Tc-99 in the FBSR product is aided by the profile of the Tc-99 concentrations over time in the SLAW. Demonstration testing should be done to assess levels of Tc-99 that could occur in the spent carbon and spent HEPA filters.

Figure D-13 shows that, like for Tc-99, the FBSR product is the only necessary disposal path for I-129; but some may also be captured in spent carbon, in the wet scrubber, and in spent HEPA filters. I-129 that is captured in the wet scrubber is recycled back the DMR, where most of it is captured in the FBSR product. With the high capture efficiency of about 89% in the FBSR product (Jantzen 2014 and THOR Treatment Technologies 2009b), significantly decreasing amounts of volatilized I-129 remain in the recycle “flywheel.” The concentration of the I-129 in the FBSR product is aided by the profile of the I-129 concentrations over time in the SLAW. Demonstration testing should be done to assess levels of I-129 that could occur in the spent carbon and spent HEPA filters.



- Highest Tc-99 conc. in feed in first ~2 yrs
- ~83% single pass Tc-99 capture in FBSR product
- Assume ~90% of remainder captured in wet scrubber, and recycled to FBSR feed, where it is increasingly captured in FBSR product
- FBSR product is the only necessary disposal pathway for Tc-99 (decreasing recycle “flywheel”)
- Need to determine how much Tc-99 is captured in spent carbon, and on HEPAs

Figure D-12 Control and disposal of Tc-99 in the FBSR process.



- Highest I-129 conc. in feed prior to 2042
- ~88% single pass I-129 capture in FBSR product
- ~90% of remainder is captured in wet scrubber, and recycled to FBSR feed, where it is increasingly captured in FBSR product
- FBSR product is the only necessary disposal pathway for I-129 (decreasing recycle "flywheel"
- Need to determine how much I-129 is captured in spent carbon, and on HEPAs

Figure D-13 Control and disposal of I-129 in the FBSR process.

D.9 MAJOR OVERALL RISKS AND OBSTACLES TO STEAM REFORMING

Major technical risks are (a) the need to mature the overall process to High for this application, and (b) the need to better demonstrate wasteform performance to enable stakeholders to consider if the mineralized wasteform is acceptable for disposal in IDF. A technology maturation plan that would include design, testing, and modeling over several years is assumed to be needed to address both of these technical risks.

Major programmatic risks are (a) the current lack of regulator acceptance for disposal in IDF, and b) the requirement of significant concurrent line-item and operational funding (which applies to all options considered). Resolution of the technical risks may help resolve the regulator and stakeholder acceptance risk.

A process and operability risk (the risk that the process cannot operate with at least 70% availability as assumed) and how it would be mitigated is shown in the flowchart of Figure D-14. In this case, two options could be available for mitigating this risk. If both options fail, then secondary option is to accept an estimated 1-yr delay to account for only 50% availability during the first three years of the feed vector. After the first three years, an availability of 50% or less is sufficient to maintain the feed vector schedule.

Other technical and programmatic risks, and one or more possible mitigations for each risk, are summarized in Table D-8.

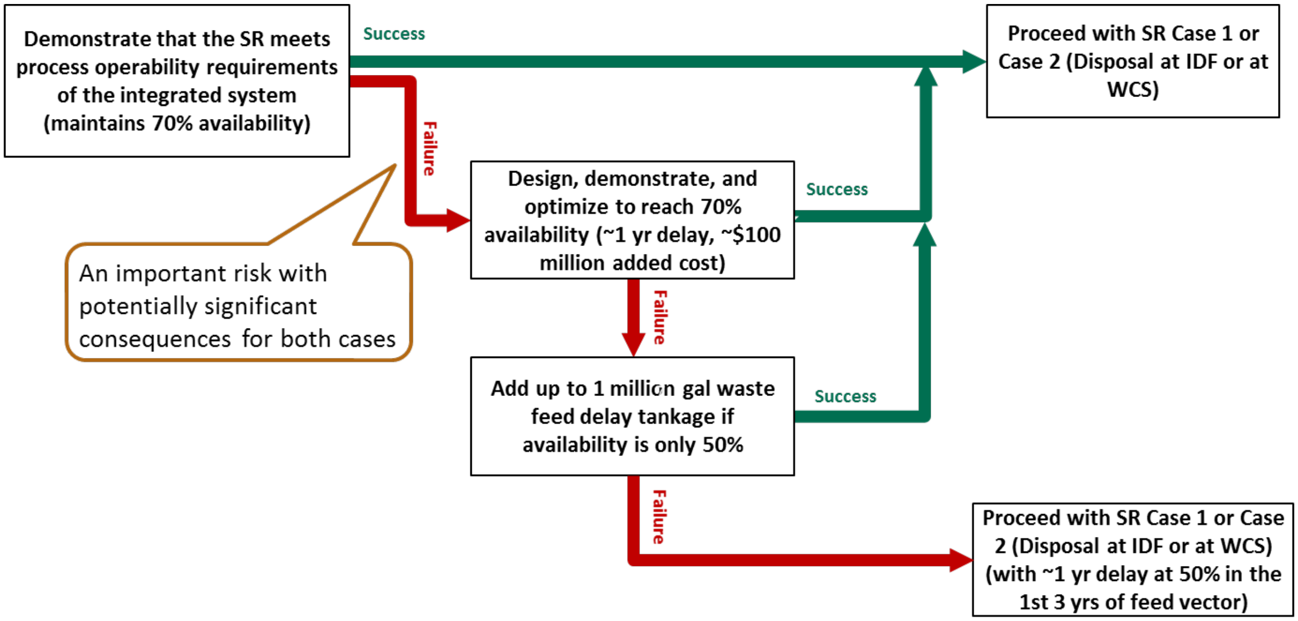


Figure D-14. FBSR operability risk and mitigations.

Table D-8 Other FBSR risks and mitigations.

Risks	Potential mitigations
1. Case 1, IDF: During demonstration testing, wasteform fails to meet IDF performance requirements.	i. Modify additives and stoichiometries. ii. Proceed with Case 2 (Disposal at WCS).
2. 2. Case 1, IDF: Partitioning of Tc-99 and I129 to HEPA filters and spent carbon is higher than can meet IDF acceptance requirements.	i. Off-gas scrubber reconfiguration. ii. Improve Tc/I retention in grouted spent carbon and filter wasteforms. iii. Proceed with Case 1 but send spent HEPAs and carbon to offsite disposal. iv. Proceed with Case 2 – WCS.
3. Case 2, WCS: Texas blocks WCS from accepting Hanford wastes	Negotiate with WA, TX, or alternate to secure viable disposal options (e.g., HIC to IDF).
4. Case 2: Political opposition to transportation halts rail shipping	Change route, shift to road/truck shipping, or alternate to secure other disposal options.

D.9.1 IWTU Startup Challenges and Resolutions

The experience of INL's IWTU is a benchmark for estimated costs, schedule, technology maturation for a FOAK facility, and identification of risks and mitigations. The IWTU pilot plant studies were started in 2005 following several years of modeling and bench-scale studies, with the benefit of the Erwin Resin*Solutions* Facility that began operations in the late 1990's. The IWTU design and construction were complete, based on the technical maturity demonstrated in several pilot tests (and the Erwin facility) and startup operations were deemed ready to commence in 2012. Various startup issues have delayed and extended startup until present (2018). Startup operations identified many modifications or other changes needed to enable or improve process subsystems, equipment, procedures, monitoring, and control, as summarized in Table D-9.

Table D-9 IWTU startup challenges and resolutions.

June 2012: Overpressurization of the IWTU system during initial IWTU heatup tests; breached filters; atmospheric release of coal and charcoal dust from the stack until process was shut down. No personnel were injured; no vessels or piping were damaged; no actual or simulated waste was used; and no radioactive or hazardous materials were in the facility or released. This caused a ~3-yr delay in IWTU startup between 2012 to 2015.
Resolution: An investigation was performed and reported in "Investigation of the Integrated Waste Treatment Unit (IWTU) Over-Pressurization Event of June 16, 2012" (Idaho Completion Project report RPT-1119, August 2012). The investigation reviewed several related causes, and made recommendations how to prevent a recurrence. The event occurred when excess coal and charcoal particles were entrained in the process gas stream, causing filter cake buildup and bridging in the PGF and the Off-gas Filter (OGF, downstream of the Carbon Reduction Reformer [CRR]). This caused excessive pressure drop across the filters that eventually caused PGF and OGF filter elements to lift off of the tubesheets, and allow unfiltered particles to pass on to, plug and breach the HEPA filter elements. When the HEPA filters breached, unfiltered coal and charcoal dust particles were released from IWTU stack. Other concurrent process responses and controls, such as the opening of a rupture disk used to prevent vessel overpressurization, also contributed to the dust release. Multiple contributing causes included (a) insufficient understanding of plant control, (b) inadequate instrumentation, monitoring, and process control, (c) no real-time mass/energy balance, (d) design deficiencies, and (e) inadequate training, oversight, and technical inquisitiveness. The IWTU startup was delayed while changes were determined, tested, and implemented, such as (a) better guidance on chemistry, hydrodynamics, operating limits, (b) a real-time mass/energy balance, (c) additional monitoring, (d) and filter vessel modifications to prevent filter element lifting, improve back-pulsing, and dust removal, (e) improved solids handling processes, and (g) improved procedures, set-points, alarms, and corrective actions. Damaged filter elements, seals, etc. were replaced. The corrective actions solved this problem. As of 2018, the IWTU has operated without a repeat of these problems during numerous startup and operational tests.
Various startup and operating issues, typical of a first-of-a-kind facility. These contributed to startup delays from 2015-2018.
Resolutions: Various startup and operating issues listed below have, to date, been resolved through equipment or operating changes. These represent lessons learned that can be incorporated into the design for SLAW treatment. The solid product handling system now operates successfully after modifying solids eductors, operating temperatures and durations, modifying fluidization pads in hoppers, etc. Flow measurement and control for input steam, nitrogen, and oxygen has been revised with some new or different flow meter and flow controller choices, added electronic logging, and procedures. Solids feed system reliability has been improved using operating and control parameters, monitoring, maintenance, and changes in the lock-hopper equipment. This is an area of continued monitoring and maintenance. The CRR solid feed systems would not be required in the concept for the SLAW design. DMR product sample collection system operability has been improved after several modifications. PGF system has been modified to reduce filter element breakage. Filter element performance continues to be evaluated following high pressure drops observed during testing in the summer of 2018. CRR refractory modifications and repairs have been done to repair cracked and spalled refractory and improve longevity during temperature cycles and startups. This will be an area for continued monitoring, repairs, and modification when needed. The FBSR design for SLAW treatment does not have this CRR design; but DMR options may include a refractory lining. CRR gas injectors were changed to improve destruction of NO_x and reduced gas species.. This CRR is eliminated in the SLAW design. Carbon bed heatup and temperature control procedures were revised to speed heatup and still prevent over-temperature. Process and off-gas blower shaft and seal design and operation were modified to increase operating life and performance. The HEPA filter element design was modified to be more rigid to prevent filter element collapse, loss of filtration surface area, and increased pressure drop. The flow control dampers were replaced with new isolation valves.
Insufficient DMR bed particle size control.
Resolutions: The DMR bed particle size distribution results from (a) particle growth as new product adds to existing particles, (b) formation of new small particles, (c) particle attrition (break-up), and (d) periodic removal of bed particles to the product handling system. When needed, alumina seed particles are added. Particle size was not well controlled in IWTU operation prior to 2017, but was successfully demonstrated in 2018. New online Fast Fourier Transform monitoring technology and sampling and analysis continue to be advanced and demonstrated with successive startup runs.
DMR bed "sandcastling" between 2016-2018 to present.
Resolutions: "Sandcastling" occurs when fluidized bed particles, in regions of low fluidizing gas velocity weakly stick together. This can cause fluidizing gas channeling and reduced mass and heat transfer. WF operations must stop when this occurs. In 2018, extensive re-design of the fluidizing gas injectors and the bottom of the bed vessel, with modeling and pilot and full-scale testing, was done to solve this. This was successfully demonstrated in the IWTU run performed during the summer of 2018.
Scale or accretion formation inside the DMR between 2016-2018 to present.
Various types of solid deposits have occurred inside the DMR. Eliminating or at least reducing these different types of deposits has required several IWTU test runs, modeling, pilot testing, equipment redesign, installation, and demonstrations.

Deposits in and around the auger-grinder plugged the auger-grinder until it was redesigned, tested, and installed, together with improved segregation of moisture and better temperature control low in the DMR. Wall scale formed during operation on in the inside surfaces of the DMR, caused by inadequate fluidization and waste conversion chemistry conditions. The modified bed fluidization design, together with chemistry modification through the WF additions, and control of particle size, bed temperature, and bed stoichiometry, has been shown in 2018 to provide needed wall scale control. Solid deposits on WF injectors can impair WF atomization into the fluidized bed. Feed injector design and optimization has been an ongoing activity during startup, to minimize deposits and maximize feed nozzle life.
PGF filter pressure drop during summer 2018 tests.
The tests performed in the summer of 2018 that demonstrated control of “sandcastling” and wall scale formation ran long enough to enable identification of increasing and unrecoverable pressure drop across the PGF filters. This issue is now being studied to assess how to manage the pressure drop in long-term operation and reduce corrosion of the Inconel 625 filters. Options being evaluated include changing the filter media and operating at lower PGF temperatures to reduce corrosion.

D.9.1.1 Underlying Issues

The startup challenges from 2012-2016 are summarized as follows (Giebel 2018a and 2018b):

- The DMR chemical reactions and hydrodynamic processes are complex and intertwined.
- Technology maturation testing, modeling and engineering assessments were not sufficient. Chemistry, kinetics, and fluidization were not adequately understood and assessed, and models were not sufficiently developed and used. This led to insufficient expertise and experience with this process, which impacted the design and initial operation.
- Risks associated with the first-of-a-kind application of steam reforming for treating the INL sodium bearing waste were not recognized. This (a) led to various flaws in the design, specifications, and procedures, and (b) contributed to mis-diagnosing test results, which lengthened the start-up and commissioning phase.
- Optimistic assumptions of operation and throughput impacted plant operability, preventive maintenance, reliability, spare parts, and redundancy.
- Several RadCon related controls and first-of-a-kind systems were not sufficiently matured, especially with respect to the solids product handling system.

D.9.1.2 Resolutions of Startup and Operating Challenges

Many system and subsystem issues with the IWTU have now been solved; startup/commissioning may soon be complete, depending on the success of resolution of the PGF filter pressure drop issue and any other identified issues. Startup of radioactive SBW treatment operations depends on satisfactory demonstration of the process, equipment, and procedures during non-radioactive operations.

Since these startup and operating issues have been or may soon be solved at IWTU, those lessons learned can help prevent similar design and operating issues at Hanford. Indeed, some of the IWTU startup issues are not expected to apply to the mineralizing steam reformer process as conceptualized to treat Hanford SLAW. The chemistry of the mineralizing process needed for Hanford SLAW, and the differences between a Hanford SLAW steam reforming process (such as elimination of the fluidized bed Carbon Reduction Reformer [CRR]) and the IWTU design, eliminates the following issues that occurred at the IWTU:

- System overpressurization, and issues related to cleanable filter operation, input gas flowrate and flow control, solids handling, carbon beds, HEPA filtration, and refractory: IWTU lessons learned will enable design and operation to avoid a repeat of this issue.
- DMR bed sandcastling and wall scale will be avoided because the mineralizing chemistry prevents these.
- CRR solid fuel feeding, refractory, and gas injection issues will be avoided by replacing this fluidized bed system with an open-chamber oxidizer.

D.10 BENEFITS OF FBSR FOR HANFORD SLAW

Benefits that steam reforming can provide for treating the Hanford SLAW include:

- Tolerance of feed vector variations and to integrated system process upsets that change the feed vector flowrate or compositions. FBSR conditions such as WF flowrate, the mineralizing chemistry, and process gas stoichiometry can be readily changed without changing equipment in response to feed vector changes. Either or both of the FBSR systems can be started up, shut down, and operated with reduced feedrate. Startup from ambient temperature standby conditions takes about 1-2 weeks to be ready for WF treatment. Emergency shutdowns can be done within minutes. Controlled shutdowns from nominal WF operation to ambient temperature standby can take about 3 days.
- The FBSR thermal process can meet best demonstrated available technology requirements similar to vitrification. The process can efficiently destroy hazardous organics, nitrates and NOx, and ammonium compounds.
- Wasteform benefits: According to recent waste tests, steam reforming can produce a durable wasteform. It does not appreciably increase waste volume during treatment, and it does not produce any liquid secondary wastes (besides equipment decontamination solution, etc.) Even equipment decontamination solution can be processed through the FBSR and eliminated, if desired. The estimated amount of equipment decon solution is about 0.04 L per L of WF; so adding this amount of decon solution does not significantly change the WF rate.

D.11 POTENTIAL OPPORTUNITIES FOR FBSR

Potential opportunities for steam reforming the Hanford SLAW include:

- Reducing or eliminating the “flywheel” concentrations of volatile and semivolatile elements (Cl, Cr, F, I, S, Tc) by recycling scrub solutions less to WTP vitrification and more to SLAW steam reforming with higher single pass control efficiencies (as shown in Table D-10). Non-volatile elements including most actinides, lanthanides, and radioactive or hazardous transition metals are captured with nominally the same or better single pass control efficiency as for Cr (99.99%).
- Multiple steam reformer systems could be either co-located (as in Cases 1 and 2) or located in different tank farm locations to reduce the need to move tank farm wastes long distances from the tank farms to a separate treatment facility location.
- Liquid secondary wastes destined for grouting could be steam reformed to replace the grouted wasteform with a ~2-100x lower-volume, durable mineralized wasteform. This large potential reduction is because liquid water, that would otherwise need to be grouted, is evaporated and discharged, after scrubbing and filtration in the off-gas control system, to the atmosphere. The only solid wasteform would be the amounts of undissolved and dissolved inorganic solids, that would be converted into the durable mineral wasteform.
- If integrated system upsets occur that cause unplanned feed vector changes, steam reforming can be started up, shut down temporarily, or operated with reduced feedrate.

Table D-10 Single pass control efficiencies for volatile and semivolatile elements.

Element	**Cl**	**Cr**	**F**	**I**	**S**	**Tc**
Single pass control efficiency, %	90%	99.99%	85%	89%	90%	83%

D.12 AREAS FOR FURTHER STUDY TO FILL IN DATA GAPS OR IMPROVE HANFORD SLAW TREATMENT OPTIONS

The following items were identified in this study as areas where further study can fill in data gaps or improve SLAW treatment options:

- Perform IDF PA for non-glass wasteforms.
- Develop consensus on how to assess performance of non-glass wasteforms.
- Update conclusions of the 2012 TC and WM EIS to account for new steam reforming wasteform performance data.
- Perform a trade study on separating more Sr-90, Tc-99, and I-129 from the LAW; and for treating ammonium and organics (although this is not necessary if steam reforming is used for SLAW treatment).
- Consider in future System Plans more LAW delay tankage to better time-average the total SLAW feed vector flowrate and composition (a mitigation for <70% process availability).
- Include shipping some or certain wastes or wasteforms to commercial sites for treatment and/or disposal as an option in future System Plans.
- Evaluate and test off-gas system process improvements to reduce liquid secondary waste generation from vitrification.
- Improve technical maturity of alternatives to vitrification and disposal in IDF. This may provide viable options for shortening tank remediation schedule and reducing costs.

D.13 SUMMARY

Fluidized bed steam reforming has been researched, demonstrated, and used for treating LLW and mixed LLW for over two decades. Multiple research, development, and demonstration programs have used bench and pilot-scale DMR systems. Two full scale FBSR facilities include the IWTU for SBW and the Erwin Resin*Solutions* Facility (formerly Studsvik Processing Facility) in Erwin, TN for LLRW and mixed LLW in the US. Studsvik continues to demonstrate FBSR for various customers.

Some desired features that steam reforming has for treating such waste streams as the Hanford SLAW include:

- Moderate temperature high enough to destroy organics and NO_x, produce a mineralized durable wasteform.
- Retain radionuclides, halogens, and hazardous metals with efficiencies high enough to be the wasteform for those elements.
- No liquid secondary wastes – can break the recycle “flywheel” especially for troublesome radionuclides Tc-99 and I-129.
- Little or no volume increase in producing the wasteform.

Issues, risks, and uncertainties that remain for FBSR treatment Hanford SLAW can be addressed with some applied development and demonstration including pilot-scale and full-scale demonstration of the integrated process that consists of multiple subsystems designed to meet the requirements for treating Hanford SLAW.

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APPENDIX E. RISK ASSESSMENT

E.1 INTRODUCTION

A semi-quantitative methodology was the basis for characterizing the program risks associated with each of the SLAW options. The methodology involved team brainstorming to systematically identify and characterize risks associated with each technology option. The approach is similar to a family of semi-quantitative methods that include FMECA (failure modes, effects and criticality analysis), HAZOPS (hazard and operability studies), preliminary hazards analysis (PHA) and What-If? studies. [Guidelines for Hazard Evaluation Procedures, CCPS, Wiley, 2008]. These methods involve group elicitation of a team of subject matter experts (SMEs) to define and quantify scenarios representing hypothetical deviations from R&D outcome, programmatic, design or operational intent. Documentation of the scenarios and their risk characterization is then systematized through use of a pre-established worksheet structure that allows direct risk comparison between scenarios and between SLAW options. The specific methodology, elicitation process, and documentation structure were designed to meet the objectives of the SLAW analysis; that is, to establish a basis for preliminary risk-informed comparison between options as currently defined.

This was not a full quantitative risk assessment of options since design and operational specifics currently available would not support that depth of analysis; that is, each option is no further developed than might be associated with CD-0. Rather, this was a semi-quantitative approach (to be described) but, importantly, adhered to a formal risk structure; that is, was based on analysis of the following triplet:

- Scenario: The combination of events that would result in deviations from design/operational/programmatic intent.
- Probability: The probability of that combination of events occurring.
- Consequences: The impact of that combination of events if it were to occur.

The consequence metrics for each scenario on which the study focused were the incremental cost and the increased duration of the tank waste treatment mission.

The intent of this appendix is to describe the methodology used in the risk assessment and to present some general, comparative results. The detailed risk worksheets are included at the end of this appendix. Specific insights gained from the risk assessment are incorporated into the report sections addressing each technology option.

E.2 METHODOLOGY

Participants in the study were SMEs and technology leads for each of the SLAW technology options. Prior to the elicitation sessions, worksheets had been designed for the documentation of (1) potential threats to successful deployment and operation of each SLAW option, (2) mitigative actions that would minimize cost and schedule impacts to the tank waste treatment mission, and (3) estimation of those cost and schedule impacts. To ensure consensus on approach, the structure of the worksheet had been discussed with and reviewed by the SMEs before the group was convened.

Table E.1 lists the column headers in each worksheet, which define the information elicited from the SMEs. In summary, for each scenario identified, the worksheet called for

- a description of its specific cause (importantly, including timing in the RD&D cycle)
- the probability of that causal event occurring

- the means of its mitigation
- the probability that the identified mitigation action would be successful
- the incremental cost and duration of the tank waste treatment mission if the mitigation fails, and
- the incremental cost and duration of the tank waste treatment mission if the mitigation succeeds.

Table E-1 Risk Worksheet Column Definitions

Column Header	Definition
Option/Variant ID	S-LAW option ID to which scenario applies
Option/Variant Name	S-LAW option description
Scenario ID	A scenario designation for reference
Cause	Event that initiates the scenario
Cause Prob	The probability rating associated with occurrence of the cause
Mitigation	Once the cause has occurred, actions that would be taken to mitigate its impact
Mitigation Prob	The probability rating associated with implementing the mitigation and its subsequent success
Unmitigated Consequences	Description of the consequences that would occur if the mitigation fails
Unmitigated Consequences: Cost	The cost impact rating of the unmitigated scenario
Unmitigated Consequences: Schedule	The schedule impact rating of the unmitigated scenario
Mitigated Consequences	Description of the residual consequences that would occur if mitigation is successful
Mitigated Consequences: Cost	The cost impact rating of the mitigated scenario
Mitigated Consequences: Schedule	The schedule impact rating of the mitigated scenario
Risk - Cost	Internally calculated central estimate of cost risk in $B
Risk - Schedule	Internally calculated central estimate of delay risk in years
Comments	Notes clarifying or justifying the scenario

The semi-quantitative aspect of the study is reflected in the ratings categories used to assess probabilities and consequence impacts for each scenario. These are shown in Table E.2. Note that the cost ratings were interpreted to exclude costs associated exclusively with schedule extension (that is, constant level-of effort costs), and were focused more on the incremental costs of R&D, deployment and operations associated with mission completion. The approach to establishing the scenario ratings was one of consensus.

Once ratings had been established for a scenario, the worksheet implements a simple calculation of incremental cost and schedule risks to allow broad risk-based comparison between scenarios, and ultimately between SLAW options.

Table E-2 Probability and Consequence Ratings

Scenario Probability/Consequence/Mitigation Ratings					
Rating	**Category**	**Cause Probability**	**Cost Consequences**	**Schedule Consequences**	**Mitigation Probability**
VH	**very high**	95 - 100%	> 5 $B	> 10 years	95 - 100%
H	**high**	40 - 95%	3 - 5 $B	7 - 10 years	40 - 95%
M	**medium**	25 - 40%	1 - 3 $B	3 - 7 years	25 - 40%
L	**low**	1 - 25%	0.1 - 1 $B	1 - 3 years	1 - 25%
VL	**very low**	<1%	< 0.1 $B	< 1 year	<1%

With each scenario, the cost risk is calculated as:

$$R = P_C \, . \, [P_M \, . \, C_M + (1 - P_M) \, . \, C_U]$$

where

P_C = cause probability
P_M = probability of successful mitigation
C_M = incremental cost to mission associated with cause, if successfully mitigated
C_U = incremental cost to mission associated with cause, if not successfully mitigated.

That is, the risk is calculated as the sum of the probability-weighted incremental costs associated with the mitigated and unmitigated cases. Mission delay risk is calculated similarly, except that C_M and C_U are now replaced by mission delay times for the mitigated and unmitigated cases. The mid-points of the Table E.2 rating category ranges were used as the basis for quantifying these risk formulas (or a representative point for unbounded rating categories). Note that the intent of this *semi-quantitative* methodology was not to achieve precision in the risk estimates but, rather, to obtain approximate, comparative risk rankings of the technology options considered.

In some cases, the mitigation logic for a scenario cause was assessed to be more complicated than that represented in this equation. In particular, if more than one mitigation option was identified for a scenario, with the assumption that each option would be deployed in the event that the previous mitigation option failed, then the formulas embedded in the worksheet were revised for such scenarios to reflect this more complicated logic. For example, the event tree in Figure E.1 shows the logic for three alternative mitigation options associated with a scenario in which, for Grout Case I, grout formulation performance fails to meet DOE O 435.1 requirements. The first mitigation option involves performing R&D to mature the grout formulation such that it is able to meet the DOE requirements. If this mitigation fails, then the second mitigation approach focuses on Tc/I separations to help meet DOE requirements. If this second mitigation approach fails then the third mitigation option is to pursue Grout Case 2 involving waste shipment offsite to WCS.

Only if this third mitigation option fails is the outcome defined as Unmitigated, in this case involving the pursuit of an alternative to grout technology. Risk formulas reflecting this and other scenarios with more complex mitigation logic were incorporated into the worksheet.

E.3 IMPLEMENTATION

Use of this methodology resulted in a set of completed worksheets for the five options under consideration:

- Grout Case 1: Grout technology with LDR pretreatment, waste to IDF
- Grout Case 2: Grout technology with LDR pretreatment, waste to WCS
- Steam Reforming Base Case: IDF waste disposal
- Steam Reforming WCS Case: Secondary waste to WCS
- Vitrification: Vit technology for SLAW.

The completed worksheets are included at the end of this appendix.

There were three scenario causes that required modification of the worksheets to accommodate multiple mitigation options. The event trees for these scenarios are shown as Figures E.1, E.2 and E.3, representing:

1. In Grout Case I: Three successive options for mitigating a scenario in which the grout formulation fails to meet DOE O 435.1 requirements (Figure E.1).

- Mitigation Option 1: Improve grout formulation.
- Mitigation Option 2: Tc/I separations to help meet DOE requirements.

- Mitigation Option 3: Send waste to WCS.
- Unmitigated: Pursue non-grout option.

2. In Grout Case I: Three successive options for mitigating a scenario in which the grout formulation fails to meet Washington State permitting requirements (Figure E.2).

- Mitigation Option 1: Improve grout formulation.
- Mitigation Option 2: Tc/I separations to help meet State requirements.
- Mitigation Option 3: Send waste to WCS.
- Unmitigated: Pursue non-grout option.

3. In Steam Reforming Base Case: Three successive options for mitigating a scenario in which partitioning of Tc-99 and I-129 to the HEPA filters and spent carbon is found in testing to exceed IDF acceptance criteria (Figure E.3).

- Mitigation Option 1: Reconfigure/redesign SLAW to incorporate scrub/recycle.
- Mitigation Option 2: Improve grouted spent carbon and filter retention.
- Mitigation Option 3: Send secondary waste to WCS.
- Unmitigated: Pursue non-steam reforming technology option.

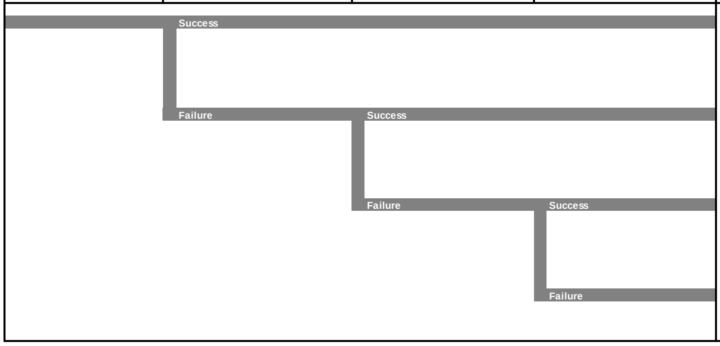
Figure E.4 shows a quantitative rollup of the identified risks for each technology option. These cost and schedule risk estimates should be interpreted as the expectation values of the increment to cost and duration of the tank waste treatment mission beyond the baseline (no risk) cost and duration associated with the technology option under consideration.

This comparative risk assessment should be considered a preliminary and approximate evaluation of the program risks posed by each option, based on the current degrees of process definition. As the designs progress beyond CD-0, the bases for modeling and quantification will evolve, and more refined methodology sets, up to full quantitative assessment, will become available. A further caveat to these results is that, like any risk assessment, the scope of the scenarios considered is incomplete for two principal reasons:

- Intended scope limitations: Certain classes of risk are considered beyond the ability of the convened experts to credibly assess, and are sometimes referred to as *Known Unknowns*. A related class of risks are those that are beyond the control of the project and so there is limited value in attempting to characterize them as a basis for risk management. These classes of risk can be captured as a list of *System Risks* or, conversely, as a list of *Enabling Assumptions* meaning that these system risks will not be addressed in the analysis. An example of a system risk is that inadequate funding is appropriated for the project. The system risks identified for the current analysis are listed in Table E.3.
- Unintended scope limitations: There is also the possibility that there are scenarios with the potential to adversely impact the tank waste mission that the assessment team has failed to identify. These can sometimes be referred to as *Unknown Unknowns* and they reflect a limitation in any risk assessment. The possibility of omitted scenarios is not, of course, associated uniquely with risk assessments, and such omissions of knowledge could adversely impact any decision-making process based on the consideration of decision consequences. However, the strength of risk assessment as a specific approach resides in its ability to provide a systematic and transparent basis for decision-making in light of the information and knowledge available.

In Section 1 of this report, uncertainties in capital and operating cost estimates are assessed for each technology option. Commensurate with the current level of design and operational specificity for each option, these cost estimates are presented as rough order-of-magnitude, based on methods consistent with DOE estimating guides. In principle, the cost uncertainties stemming from the risks identified in this appendix could be integrated, in future, into an overall cost uncertainty assessment. This will require sufficient design specificity be available to support a full probabilistic analysis of both estimating uncertainty and of risk.

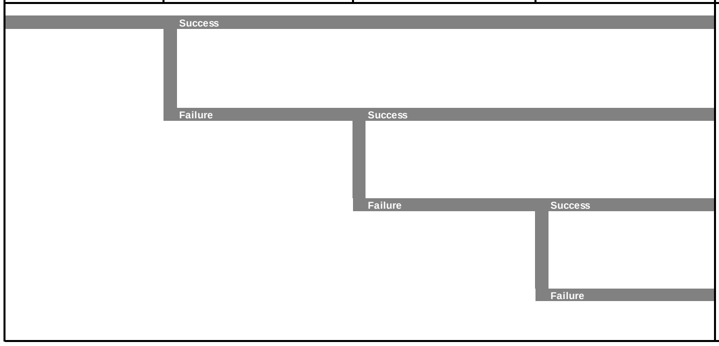
CAUSE	MITIGATION 1	MITIGATION 2	MITIGATION 3	Scenario Description	Scenario Probability	Cost Consequence	Schedule Consequence
Grout Case I - Failure to Meet O 435.1	Additional R&D - Improve Grout	Go to Option 2E1 - TC/I Separations	Go to Option Grout II - Waste to WCS				
Probability PC: H	Success Probability PM1: VH	Success Probability PM2: H	Success Probability PM3: H				



Scenario Description	Scenario Probability	Cost Consequence	Schedule Consequence
First Mitigation Option Succeeds	PC . PM1	VL	VL
Second Mitigation Option Succeeds	PC. (1-PM1). PM2	L	VL
Third Mitigation Option Succeeds	PC. (1-PM1) . (1-PM2) . PM3	M	L
Pursue Non-Grout Technology	PC. (1-PM1) . (1-PM2) . (1-PM3)	VH	VH

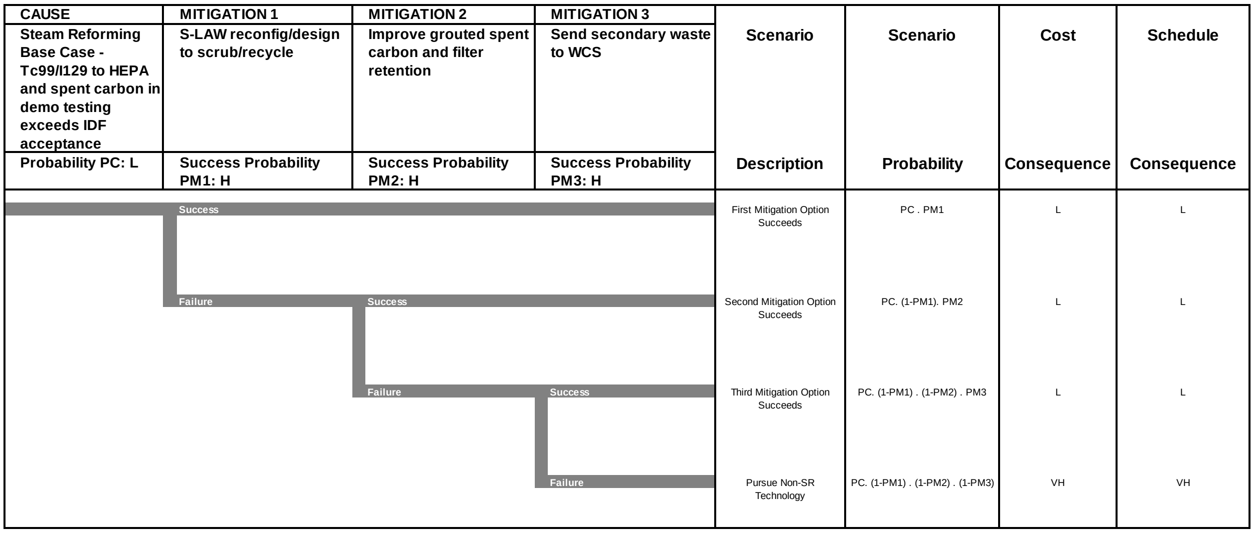
Figure E-1. Event Tree for Multiple Mitigation Options – Grout Case I. Failure to meet DOE O 435.1 grout performance requirements.

CAUSE	MITIGATION 1	MITIGATION 2	MITIGATION 3	Scenario Description	Scenario Probability	Cost Consequence	Schedule Consequence
Grout Case I - Failure to Meet State Permitting Requirements	Additional R&D - Improve Grout	Go to Option 2E1 - TC/I Separations	Go to Option Grout II - Waste to WCS				
Probability PC: VH	Success Probability PM1: L	Success Probability PM2: H	Success Probability PM3: H				



Scenario Description	Scenario Probability	Cost Consequence	Schedule Consequence
First Mitigation Option Succeeds	PC . PM1	VL	VL
Second Mitigation Option Succeeds	PC. (1-PM1). PM2	L	VL
Third Mitigation Option Succeeds	PC. (1-PM1) . (1-PM2) . PM3	M	L
Pursue Non-Grout Technology	PC. (1-PM1) . (1-PM2) . (1-PM3)	VH	VH

Figure E-2. Event Tree for Multiple Mitigation Options – Grout Case I. Failure to meet State permitting grout performance requirements.



CAUSE	MITIGATION 1	MITIGATION 2	MITIGATION 3	Scenario Description	Scenario Probability	Cost Consequence	Schedule Consequence
Steam Reforming Base Case - Tc99/I129 to HEPA and spent carbon in demo testing exceeds IDF acceptance	S-LAW reconfig/design to scrub/recycle	Improve grouted spent carbon and filter retention	Send secondary waste to WCS				
Probability PC: L	Success Probability PM1: H	Success Probability PM2: H	Success Probability PM3: H				
				First Mitigation Option Succeeds	PC . PM1	L	L
				Second Mitigation Option Succeeds	PC. (1-PM1). PM2	L	L
				Third Mitigation Option Succeeds	PC. (1-PM1) . (1-PM2) . PM3	L	L
				Pursue Non-SR Technology	PC. (1-PM1) . (1-PM2) . (1-PM3)	VH	VH

Figure E-3 Event Tree for Multiple Mitigation Options – Steam Reforming Base Case. Tc-99/I-129 to HEPA and spent carbon in demo testing exceeds IDF acceptance.

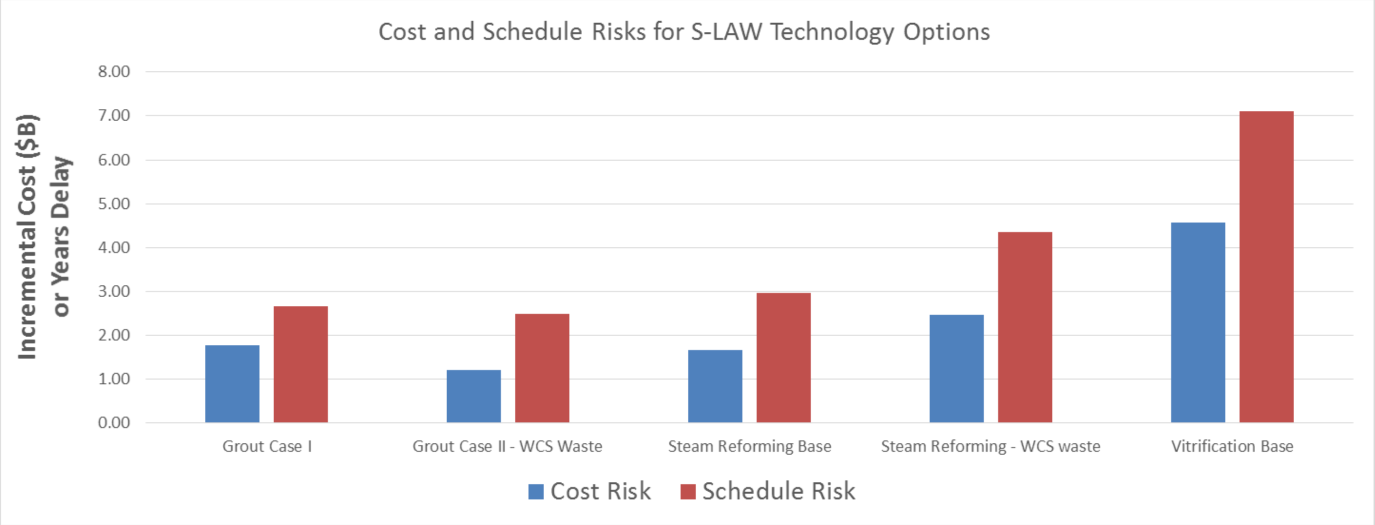


Figure E-4 Incremental Mission Cost and Duration Risks for Each Technology Option. These are the expectation values of risk-based incremental cost and duration associated with the tank waste mission relative to the baseline of each SLAW technology option.

Table E-3 System Risks: Not captured in the risk worksheets

Supplemental LAW cannot be constructed due to competing funding demands from WTP-PT and WTP-HLW. Or SLAW is delayed by WTP start-up and operations cost.
The funding profile (operating) provided is not sufficient to perform scope as specified in SP8 resulting in extended mission costs and schedule.
WTP-PT is not completed and replaced by a direct feed option which changes the feed vector size and composition for SLAW.
Direct Feed High-Level Waste option is implemented which changes the feed vector size and composition for SLAW.
Modular systems replace WTP-PT which changes feed vector size and composition for SLAW.

Retrieval rates are insufficient to feed treatment plants, testing operational flexibility of technology options and extending mission schedule.
Inaccurate compositions provided by BBI data resulting in out-of-spec feed.
Inaccurate compositions and amounts used for waste estimation resulting in out-of-spec feed.
Volume to be processed through Supplemental LAW changes, testing operational flexibility of technology options and extending mission schedule.
Comparative cost estimates between technology options are significantly inaccurate (but uncertainties considered likely to be small compared to cost differentials between options).

The completed risk assessment worksheets are shown in Table E.4.

Table E-4 Risk Worksheets

Grout

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S-LAW Grout Case I and Grout Case II

Option/Variant		**Scenario ID**	**Cause**	Cause Prob	**Mitigation**	Mitigation Prob	**Unmitigated Consequences**	Unmitigated Consequences		**Mitigated Consequences**	Mitigated Consequences		Risk Calc		Comments
ID	Name							Cost	Schedule		Cost	Schedule	Cost Risk ($B)	Schedule Risk (Yrs)	
2D	Grout Case I (2D)	REG 3a	Grout formulation- performance unable to meet DOE performance requirements (435.1)	H	Mitigation attempt 1: Mature grout formulation and getters to demo acceptable grout performance, PA special analysis, container credit	VH	See mitigation below			Cost and delay associated with designing formulation maturation	VL	VL			Cause - during process design; mitigation occurs as part of base case. Consider container credit. Unmitigated cost the $2B cost of rail transport/disposal at WCS. VL schedule impact on mitigated or unmitigated. Mitigated includes 3-7 years development prior to startup - no impact on mission schedule
					Mitigation attempt 2: Pursue Option 2E1/2 (Tc/I Separations)	H	See mitigation below			Cost and delay associated with designing formulation maturation, and then with Tc/I separations	L	VL			L for Schedule depends on I-129 - TRL or regulatory solution?. Mitigation schedule assumes 3-7 years available before startup, so VL impact on schedule. Cause occurs during process design.
					Mitigation attempt 3: Pursue Option 2G2 (to WCS)	H	Cost and delays associated with pursuit of alternative non-grout technology	VH	VH	Cost and delay associated with designing formulation maturation, and then with Tc/I separations, and then with shipping offsite	M	L	0.05	0.10	
2D	Grout Case I (2D)	REG 3b	Grout formulation- performance unable to meet Tc/I ECY performance expectations/State permitting requirements - given DOE requirements are met	VH	Mitigation attempt 1: Mature grout formulation and getters to demo acceptable grout performance, PA special analysis, container credit	L	See mitigation below			Cost and delay associated with designing formulation maturation	VL	VL			L for Schedule depends on I-129 - TRL or regulatory solution?. Mitigation schedule assumes 3-7 years available before startup, so VL impact on schedule. Cause occurs during process design.
2D					Pursue Option 2E1/2 (Tc/I Separations)	H	See mitigation below			Cost and delay associated with designing formulation maturation, and then with Tc/I separations	L	VL			L for Schedule depends on I-129 - TRL or regulatory solution?. Mitigation schedule assumes 3-7 years available before startup, so VL impact on schedule. Cause occurs during process design.
2D					Pursue Option 2G2 (to WCS)	H	Cost and delays associated with pursuit of alternative non-grout technology	VH	VH	Cost and delay associated with designing formulation maturation, and then with Tc/I separations, and then with shipping offsite	M	L	1.32	1.61	Unmitigated consequences for Reg 3A and 3B same. Unmitigated consequence assumes Vit baseline as non-grout option. >5B cost, and 3-7 years delay - start up vit design. Mitigated - $2B costs, 1-3 years including possible NEPA
2D	Grout Case I	PT 5a	During operation it is determined that for a range of tank compositions non thermal oxidative methods do not result in sufficient LDR organic destruction	M	Divert problematic waste streams to LAW VIT - able to swap other waste to balance SLAW and LAW VIT - no impact on schedule.	H	Diverts to LAW VIT, but more waste causes delay in schedule, inability to balance SLAW and LAW VIT	M	M	Cost of vitrifying fraction of LAW stream that was planned to go to grout	VL	VL	0.22	0.55	Unmitigated, Assuming a fraction of tanks have elevat3d organics that require diversion, possibly 1-3 years of operation and up to $3B in costs.
All	Grout Cases I and II	GRT 1	Key grout reagents become unavailable in the future	VH	Stockpile reagents and/or qualify alternative grout reagents	VH	Cost and delays associated with pursuit of alternative non-grout technology - extended operation of LAW and HLW Vit	VH	VH	Reagent stockpile and identification & qualification of alternate reagents	VL	VL	0.20	0.41	Applies to all grout cases. Given timeframe of processing, fly ash supply will become limited over time with H to VH probability. Will build this into grout options as part of the development process to assess and qualify reagents.
													1.78	2.67	
2G2	Grout Case II (2G2)	REG 1	Due to changing political considerations, Texas regulator blocks WCS from accepting Hanford wastes	L	Negotiations with WA, TX, or alternate to secure viable disposal options	M	Cost and delays associated with pursuit of alternative non-grout technology - extended operation of LAW and HLW Vit	VH	VH	Cost and delay associated with negotiations and possible added facility/process mods	M	L	0.70	1.23	Mitigation may include special cells, separating Sr90 to allow for Class A to Utah. Unmitigated consequence - if during design/development, could go to Vit baseline. If at startup or after, could consider longer operation of existing facilities vs. second vit facility. Cause is assumed to occur at/after startup of grout facility. Inherent assumption that grout started, that if TX/UT won't take it, can negotiate small volume treated so far goes to IDF with understanding remaining waste goes to LAW VIT Mitigated consequence assumes negotiation for disposal incorporates extra cost (e.g., $1B plus cost).
2G2	Grout Case II (2G2)	TRP 8	Political opposition, in major city, on rail route following a rail accident. Result may be that DOE temporarily abandon rail shipping. Occurs after shipping has started.	L	Change/renegotiate route, or shift to road/truck shipping, or alternate to secure viable disposal options	VH	Cost and delays associated with pursuit of alternative non-grout technology - extended operation of LAW and HLW Vit	VH	VH	Cost and delay associated with implementing mitigation	L	L	0.09	0.30	Cause - Assumes an accident occurs and triggers outcry. Is road/truck shipping (mitigation) subject to similar risk as rail? - many more options (routes) by truck, and not significantly more expensive. Transportation costs are not appreciable relative to disposal costs. First priority negotiate, then truck, and finally alternate disposal site where Sr90 would need to be removed. Mitigation consequences assume most conservative (alt. disposal). Same unmitigated case as Reg. 1
2G2	Grout Case II	PT 5b	During operation it is determined that for a range of tank compositions non thermal oxidative methods do not result in sufficient LDR organic destruction	M	Divert problematic waste streams to LAW VIT - able to swap other waste to balance SLAW and LAW VIT - no impact on schedule.	H	Diverts to LAW VIT, but more waste causes delay in schedule, inability to balance SLAW and LAW VIT	M	M	Cost of vitrifying fraction of LAW stream that was planned to go to grout	VL	VL	0.22	0.55	Unmitigated, Assuming a fraction of tanks have elevat3d organics that require diversion, possibly 1-3 years of operation and up to $3B in costs.
All	Grout Cases I and II	GRT 1	Key grout reagents become unavailable in the future	VH	Stockpile reagents and/or qualify alternative grout reagents	VH	Cost and delays associated with pursuit of alternative non-grout technology - extended operation of LAW and HLW Vit	VH	VH	Reagent stockpile and identification & qualification of alternate reagents	VL	VL	0.20	0.41	Applies to all grout cases. Given timeframe of processing, fly ash supply will become limited over time with H to VH probability. Will build this into grout options as part of the development process to assess and qualify reagents.
													1.21	2.48	

Steam R.

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Steam Reforming

Option/Variant		**Scenario ID**	**Cause**	Cause Prob	**Mitigation**	Mitigation Prob	**Unmitigated Consequences**	Unmitigated Consequences		**Mitigated Consequences**	Mitigated Consequences		Risk Calc		**Rec #**
ID	Name							Cost	Schedule		Cost	Schedule	Cost Risk ($B)	Schedule Risk (Yrs)	Comments
3	Steam Reforming Base Case	SR 3	Results from pilot and/or full-scale demonstrations show that SR cannot treat SLAW to meet process operability requirements of the integrated system. [can't keep up with the feed vector]	L	Design, demonstration, and optimization of SR subsystems will require additional time and costs beyond the current pilot and full-scale demonstration	H	Cost and delays associated with operating at a fraction of intended processing rate, or pursuit of alternative non-SR technology	VH	M	Cost and delay to perform additional facility testing	VL	L	0.30	0.39	Pause in design/construction to resolve facility performance - 1 year, less than $100M?; Unmitigated, not abandonment, but not run as high of throughput so estimated at 3-7 year schedule delay.
3	Steam Reforming Base Case	Modified SR 1	Partitioning of Tc99 and I129 to HEPA filters and spent carbon during demonstration testing is found to be higher than can meet IDF acceptance requirements	L	Mitigation attempt 1: SLAW treatment system re-configuration/design to scrub and recycle	H	See mitigation below			Cost and delay to reconfigure scrub/recycle	L	L			Mitigation <1B, but not insignificant due to rad facility mods.
					Mitigation attempt 2: improve grouted spent carbon and filter retention;	H	See mitigation below			Cost and delay to reconfigure scrub/recycle, and then improve grouted secondary waste	L	L			Mitigation <1B and VL schedule to adopt improved grouted secondary waste methods.
					Mitigation attempt 3: Send secondary waste offsite (to WCS)	H	Cost and delays associated with pursuit of alternative non-SR technology	VH	VH	Cost and delay to reconfigure scrub/recycle, improve grouted secondary waste and then associated shipping and disposing of secondary waste offsite	L	L	0.10	0.31	
3	Steam Reforming Base Case	SR 2	Demonstration testing results less than 70% availability (design basis) for facility	H	Include additional waste feed delay tankage; and selected process modifications to improve availability	H	Mission extension	H	M	Cost and schedule to increase tankage and selected mods	L	L	1.13	2.01	
3	Steam Reforming Base Case	SR 5	During demonstration testing, waste form fails to meet IDF performance requirements	L	Additional R&D on additives and stoichiometries with confirmation during demonstration testing	H	Dispose to WCS - Cost and delay associated with shipping offsite	M	L	R&D costs and schedule with additional confirmation testing	L	L	0.13	0.26	Mitigated - $1B costs for disposal, 1-3 years including possible NEPA
													1.66	2.96	
3B	Steam Reforming to WCS	SR 3	Results from pilot and/or full-scale demonstrations show that SR cannot treat SLAW to meet process operability requirements of the integrated system. [can't keep up with the feed vector]	L	Design, demonstration, and optimization of SR subsystems will require additional time and costs beyond the current pilot and full-scale demonstration	H	Cost and delays associated with operating at a fraction of intended processing rate, or pursuit of alternative non-SR technology	VH	M	Cost and delay to perform additional facility testing	VL	L	0.30	0.39	Pause in design/construction to resolve facility performance - 1 year, less than $100M?; Unmitigated, not abandonment, but not run as high of throughput so estimated at 3-7 year schedule delay.
3B	Steam Reforming to WCS	SR 2	Demonstration testing results less than 70% availability (design basis) for facility	H	Include additional waste feed delay tankage; and selected process modifications to improve availability	H	Mission extension	H	M	Cost and schedule to increase tankage and selected mods	L	L	1.13	2.01	
3B	Steam Reforming to WCS	REG 1	Due to changing political considerations, Texas regulator blocks WCS from accepting Hanford wastes	L	Negotiations with WA, TX, or alternate to secure viable disposal options (e.g., HIC to IDF)	M	Cost and delays associated with pursuit of alternative technology - extended operation of LAW and HLW Vit	VH	VH	Cost and delay associated with negotiations and possible added facility/process mods	M	L	0.70	1.23	Mitigation may include special cells. Unmitigated consequence - if during design/development, could go to Vit baseline. If at startup or after, could consider longer operation of existing facilities vs. second vit facility. Cause is assumed to occur at/after startup of SR facility. Inherent assumption that SR started, that if TX won't take it, can negotiate small volume treated so far that goes to IDF with understanding remaining waste goes to LAW VIT Mitigated consequence assumes negotiation for disposal incorporates extra cost (e.g., $1B plus cost).
3B	Steam Reforming to WCS	TRP 8	Political opposition to transportation along rail route. Result may be that DOE halts rail shipping. Occurs after shipping has started.	L	Change/renegotiate route, or shift to road/truck shipping, or alternate to secure viable disposal options	H	Cost and delays associated with pursuit of alternative technology - extended operation of LAW and HLW Vit	VH	VH	Cost and delay associated with implementing mitigation	L	L	0.34	0.72	Transportation costs are not appreciable relative to disposal costs. First priority negotiate, then truck, and finally alternate disposal site . Mitigation consequences assume most conservative (alt. disposal). Same unmitigated case as Reg. 1
													2.47	4.34	

VIT.

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Vitrification

Option/Variant		**Scenario ID**	**Cause**	Cause Prob	**Mitigation**	Mitigation Prob	**Unmitigated Consequences**	Unmitigated Consequences		**Mitigated Consequences**	Mitigated Consequences		Risk Calc		**Rec #**
ID	Name							Cost	Schedule		Cost	Schedule	Cost Risk ($B)	Schedule Risk (Yrs)	Comments
1, 1C	Vit Baseline 1	VIT 2	WTP LAW throughput (70% TOE) not achieved in actual operations	H	Redesign of SLAW vit baseline to meet throughput requirements	VH	Mission extension	VH	H	Delay and cost impact associated with SLAW redesign	H	M	2.75	3.43	Risk (Cause) High for equivalent risk identified in DFLAW. [need to confirm rating definitions for DFLAW risk list]. VH to M mitigated consequence cost reflects cost of redesign and addition of X melters. Range is dependent on systems needing redesign. Cannot know how far off actual LAW VIT TOE will be, so assume H to VH impact that requires at least one additional melters
1,1C	Vit Baseline 1	VIT 1	WTP LAW Startup results in facility mods that must also be implemented in SLAW VIT	M	Implement LAW VIT changes into SLAW VIT - design, fab, install	VH	Mission extension	H	M	Delay and cost impact associated with SLAW design changes	M	M	0.67	1.63	M mitigated consequence cost reflects cost of redesign., partially mitigated by pilot plant. Range is dependent on systems needing redesign
1, 1C	Vit Baseline 1	VIT 3	GFCs that were used to develop the materials handling systems and waste form are not available	L	Identify and qualify alternative sources of all GFCs	VH	Lower waste loading glasses produced	M	L	Cost and schedule of identifying/qualifying alternative GFCs	VL	VL	0.01	0.02	
1, 1C	Vit Baseline 1	VIT 4	DFs found to be lower than projected, based on DFLAW startup results and piloting of SLAW, with impact increasing burden to EMF and recycle (Tc99 and I129, and Hg)	VL	Assess/develop/implement alternate separations or disposition paths for melter offgas carryover	VH	Increased Tc99, I129 to LSW, impacting acceptability of LSW disposal in IDF	M	L	cost and schedule of identifying/qualifying alternative separations or disposition paths	L	L	0.00	0.01	Tc99 and I129 carryover to secondary waste. Have they bounded in the Integrated Flowsheet the DFs for CoCs? Risk is that they are not bounded. Tc99 may be particularly problematic, because WESP deluge not included (but WESP not in SLAW VIT). I129 potential problem because LAW VIT and SLAW VIT don't currently have effective solution for it.
1, 1C/D/G	Vit Baseline 1	VIT 5	Melter idling during actual operations of SLAW significantly decreasing waste loading (S and halides) and increases LSW volume and Tc99 levels	H	Assess/develop alternate retrieval and processing and disposal strategies (including breaking recycle) to reduce melter idling or reduce waste to IDF	H	Increased Tc99 to LSW, impacting acceptability of LSW disposal in IDF	M	L	cost and schedule associated with implementing alternate disposal and processing strategies	L	L	0.69	1.35	L to M mitigated consequence cost WTP analysis - risk tied to outage assumptions, 2-days/wk = 20% increase. Mitigation will have H effective on waste loading, but requires alt disposal to mitigate LSW impacts
1, 1C/G	Vit Baseline 1	VIT 7	Grout raw materials for LSW and SSW are not available	VH	Identify and qualify alternative sources of all SW raw materials	VH	LERF at full capacity, LAW and HLVIT require shut down until risk mitigated.	VH	VH	Reagent stockpile and identification & qualification of alternate reagents	VL	VL	0.20	0.41	Similar to GRT 1 risk. But HLVIT and LAW VIT eventually waterlogged and must shut down until resolved. Assume 2 year time frame to address if not mitigated in advance.
1, 1C	Vit Baseline 1	VIT 8	Advance glass compositions being developed to meet SP8 throughput, do not meet ECY performance expectations/permitting requirements	L	Resort to baseline glasses, lower waste loading	VH	Reduce risk budget attributed to LAW glasses disposed in IDF	L	VL	cost and schedule associated with increased LAW VIT canisters during high demand period of the feed vector	M	L	0.26	0.25	M/L mitigation cost/schedule because short period 1-3 years when increased canisters will be produced, and potential schedule impact.
													4.57	7.10	
1D/G	Bulk Vit	VIT 10	Bulk Vit pilot testing results indicate ERP issues and concerns not fully resolved	L	Additional development and testing to fully resolve key process issues	H	Cost and delays associated with pursuit of alternative technology - extended operation of LAW and HLW Vit	VH	VH	Cost and schedule for development and additional pilot testing	L	VL	0.34	0.56	Unmitigated consequence VH - extended WTP or second LAW VIT.
1D/G	Bulk Vit	VIT 11	Tc release from bulk vit containers are found to exceed projected levels	L	Additional development and testing to fully resolve key process issues	H	Cost and delays associated with pursuit of alternative technology - extended operation of LAW and HLW Vit	VH	VH	Cost and schedule for development and additional pilot testing	L	VL	0.34	0.56	
													0.69	1.12	

APPENDIX F. DISPOSAL

F.1 INTRODUCTION

This Appendix describes two disposal facilities that are being considered for disposal of the immobilized SLAW. The first facility, the Integrated Disposal Facility (IDF), is onsite at Hanford and is being developed by the DOE. The second disposal facility, the Waste Control Specialists (WCS) facility, is outside the state of Washington and is a commercially-operated disposal facility licensed by the State of Texas (a NRC Agreement State[85]).

These two facilities present diverse options, where one facility can provide safe disposal of wastes with higher concentrations of I-129 and Tc-99, but the wastes must be shipped 2200 miles for that disposal, whereas the onsite facility is more limited in its ability to fully accommodate wastes with higher concentrations of I-129 and Tc-99, but no offsite shipping is required.

In addition to the WCS disposal facility, the DOE has shipped large quantities of radioactive waste to the Clive radioactive waste disposal facility, which is in the West Desert of Utah approximately 75 miles (120 km) west of Salt Lake City. The Clive disposal facility is commercially-operated facility that is licensed by the State of Utah (also an NRC Agreement State) and the EPA to dispose of LLW and mixed LLW (MLLW). The NRC Agreement States utilize State versions of the NRC's 10 CFR 61 standard for licensing LLW disposal facilities, which divides LLW into "classes," with Class A wastes being the least hazardous and Class-C wastes being the most hazardous.

As detailed in Section F.5.4.3, the immobilized SLAW will classify as Class B and C MLLW for offsite disposal (no Class A). The Clive facility can accept only Class A LLW and MLLW for disposal; therefore, the Clive facility will not be discussed further. Should the Sr-90 be removed from the SLAW, the immobilized wasteforms (WFs) would then be classified as Class A MLLW (Section F.5.6), and Clive would be a viable offsite alternative to WCS, with a shorter shipping distance and competitive disposal fees for Class A.

The remainder of this Appendix is divided into three major subsections and begins with a review of the characteristics of the SLAW WFs requiring disposal, followed by a subsection addressing disposal at the IDF and a subsection addressing disposal at the WCS facility in west Texas. The general layout of the latter two subsections is similar, beginning with a description of the facility, followed by a review of key regulatory requirements. Because there is no radiological waste acceptance criteria (WAC)[86] for the IDF, this Appendix presents the results of a performance evaluation conducted by the FFRDC team of disposal of primary and secondary WFs in the IDF. The WCS facility does have a radiological WAC, which is presented and used to classify the primary and secondary wastes for disposal. Disposal cost considerations for the WCS are addressed in Section F.5.5.

F.2 EVALUATION ASSUMPTIONS

For this analysis, current conditions are assumed to prevail. This means that the analysis is based on current WAC for WCS, and the likely WAC for the IDF. Basing the analyses on current conditions prevents undue speculation about future conditions, while allowing an even-handed comparison of disposal at the two facilities. Where additional capacity might be needed, it is assumed that the additional capacity could be created within the existing facility boundaries, under existing (or similar) operating permits, licenses and costs.

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[85] Agreement States are states that have assumed specific regulatory authority under the Atomic Energy Act of 1954, as amended (AEA). Section 274 of the AEA provides a statutory basis under which the NRC relinquishes to the Agreement States portions of its regulatory authority to license and regulate byproduct materials, source materials (uranium and thorium), and certain quantities of special nuclear materials.

[86] As used here, WAC are the criteria the wastes must meet to be acceptable for disposal.

F.3 WASTEFORM CHARACTERISTICS IMPORTANT FOR DISPOSAL

F.3.1 Characteristics of Wastes to be Immobilized

The characteristics of the SLAW (Feed Vector) that will be immobilized for disposal are described in the One System River Protection Project Integrated Flowsheet, which is based on the assumptions in River Protection Project System Plan 8. The supplemental wastes are derived from tank wastes that have been pretreated in one of two pretreatment facilities, the WTP-PT and the LAWPS. The Feed Vector presents information for the timeframe of January of 2034 through February of 2063, a 29-year period. However, the production of significant volumes of SLAW does not begin until December 2034; therefore, the SLAW will be immobilized over a *337-month* (28-year) time-period[87].

The Feed Vector provides very detailed, projected information on the radiological characteristics of the SLAW, which is important, as the Feed Vector describes the input to the immobilization facility for vitrification, or steam reforming or grouting. The information in the Feed Vector includes:

- The monthly volume of SLAW produced by pretreatment in the WTP-PT and in the LAWPS, and
- *The specific activity of 47 nuclides from each pretreatment facility, for each month of operation*.

The Feed Vector also provides useful summary statistics, including:

- The average specific activity of each of the 47 nuclides across the 28 years
- The highest and lowest specific activity of each nuclide across the 28 years, and
- The highest volume of SLAW produced in one month and the lowest volume in one month.

As an example of the information in the Feed Vector, Table F-1 provides the radiological composition of the SLAW from the operation of the WTP-PT for the month of April 2060. *Similar data is available for every month of pretreatment operations*.

Table F-1 Example: Radiological Content - SLAW from WPT PT for April 2060

Nuclide	**Ci/m3**		**Nuclide**	**Ci/m3**		**Nuclide**	**Ci/m3**
Ru-106	3.80E-22		Th-229	7.70E-09		Pu-242	4.10E-08
Cd-113m	8.60E-05		Pa-231	7.60E-07		Am-243	1.90E-06
Sb-125	4.10E-10		Th-232	1.40E-08		Cm-243	5.00E-07
Sn-126	9.90E-05		U-232	1.60E-07		Cm-244	5.40E-06
I-129	4.30E-05		U-233	1.60E-05		H-3	7.20E-05
Cs-134	3.80E-15		U-234	1.10E-05		Ni-59	9.00E-05
Cs-137	4.90E-03		U-235	4.50E-07		Ni-59	9.00E-05
Ba-137m	0.0+0		U-236	2.40E-07		Co-60	2.90E-07
C-14	2.20E-03		Np-237	7.90E-06		Ni-63	5.60E-03
Sm-151	2.3-02		Pu-238	1.00E-04		Se-79	4.90E-04
Eu-152	7.10E-07		U-238	1.00E-05		Sr-90	8.50E-01
Eu-154	3.93E-06		Pu-239	1.60E-03		Y-90	0.00E+00
Eu-155	8.50E-08		Pu-240	3.50E-04		Zr-93	3.60E-04
Ra-226	2.40E-09		Am-241	4.10E-03		Nb-93m	4.10E-04
Ac-227	2.21E-07		Pu-241	2.20E-04		Tc-99	8.90E-02
Ra-228	1.20E-08		Cm-242	3.80E-05			

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[87] It is assumed that the small volumes of Feed from the WTP-PT, for January 2034 and February 2034, would be held and combined with the Feed from December 2034 for the first immobilization activity.

Summary statistics are also available in the Feed Vector, and Table F-2 presents the *average radiological content* of all the combined SLAW from the WPTP-T and LAWPS for the 28 years of operations. As shown in Table F-2, (on average), a single nuclide, Sr-90, is responsible for 81% of the total activity. Samarium-151 is responsible for approximately 12%, Tc-99 is responsible for 3%. Of the 47 nuclides tracked in the Feed Vector, three nuclides account for 96% of the activity and the sum of the remaining 44 nuclides account for the remaining 4% of the activity.

Table F-2 Average Radiological Content of all SLAW from combined WPT PT & LAWPS Operations

Nuclide	**Ci/m3**		**Nuclide**	**Ci/m3**		**Nuclide**	**Ci/m3**
Ru-106	6.40E-14		Th-229	7.80E-08		Pu-242	1.60E-07
Cd-113m	5.30E-04		Pa-231	2.40E-06		Am-243	3.60E-06
Sb-125	2.10E-06		Th-232	1.90E-07		Cm-243	1.40E-06
Sn-126	6.20E-04		U-232	7.00E-07		Cm-244	2.00E-05
I-129	5.40E-05		U-233	7.50E-05		H-3	3.10E-04
Cs-134	2.90E-11		U-234	2.60E-05		Ni-59	5.40E-04
Cs-137	1.00E-02		U-235	1.10E-06		Co-60	1.50E-05
Ba-137m	0.0+0		U-236	7.00E-07		Ni-63	3.50E-02
C-14	1.70E-03		Np-237	2.00E-05		Se-79	1.00E-03
Sm-151	2.30E-01		Pu-238	1.10E-04		Sr-90	1.50E+00
Eu-152	1.10E-05		U-238	2.50E-05		Y-90	0.00E+00
Eu-154	1.40E-04		Pu-239	2.80E-03		Zr-93	1.90E-03
Eu-155	1.40E-05		Pu-240	5.80E-04		Nb-93m	1.90E-03
Ra-226	6.00E-09		Am-241	7.20E-03		Tc-99	5.40E-02
Ac-227	1.50E-06		Pu-241	9.60E-04			
Ra-228	2.30E-07		Cm-242	2.40E-05		Total	1.85

Importantly, the maximum resolution available in the Feed Vector is the monthly values – therefore all analyses are based on the monthly values provided by the Feed Vector – no greater resolution is available.

If both pretreatment facilities (WTP-PT and LAWPS) operated every month over the 337 months, there would be 674 combined months of operations and 674 discrete sets of monthly Feed Vector data. However, neither facility operates full-time, *and there are 441 combined months of operations, with the associated 441 Feed Vector datasets for analysis.* This is important when the Feed Vector data is used to determine how the final WFs will classify for disposal at the WCS, as there are 441 discrete sets of Feed Vector data for waste classification.

Table F-3 provides summary statistics from the Feed Vector for the *volume of SLAW* that will be immobilized and disposed of, a total of 54,000,000 gallons (204,400 m3).

Table F-3 Summary Statistics for the Volume of SLAW to be Treated and Disposed

Total volume of SLAW to be immobilized	54,000,000 gallons (204,400 m3)
Average monthly volume (= total volume/337 months)	160,000 gallons (607 m3)

In all cases, the immobilization processes will generate solid secondary waste (SSWs). The SSW from LAW treatment includes HEPA filters and Carbon Absorber (i.e., Granular Activated Carbon). The HEPA filters and Carbon Absorber have most of Tc-99 and I-129 that is not in the primary WF. It is assumed that all SSWs will be grouted prior to disposal.

In three "variant" cases, specific nuclides will be removed from the SLAW feed stream prior to immobilization. The three variants that will generate pretreatment waste (PWs) are 2e1, 2e2 and 2f. As an example, for variant 2e2, Tc-99 and I-129 will each be selectively removed from the feed stream using ion exchange resin, prior making grout. For variant 2e2, the PWs will be grouted, transported and disposed at WCS in B-25 boxes. This variant (2e2) is the only variant where PWs will be shipped offsite and disposed at WCS.

Finally, the high temperatures of vitrification may transfer a portion of the volatile nuclides to the solidified liquid secondary waste (LSW).

F.3.2 Characteristics of the Vitrified Wasteform and Secondary Wastes

Vitrification and the vitrified WF are detailed in Appendix B. The specific characteristics important for using the Feed Vector to characterize the vitrified WF for disposal are presented in Table F-4.

Table F-4 Characteristics of the Vitrified Wasteform – Canister

Volume change caused by vitrification	*0.4* (decreases volume & increases specific activities)
Density of final WF	2800 kg/m3 (175 lb/ft3)[88]
Solid Secondary Wastes	detailed in F.5.4.4 Classifying Secondary WFs
Pretreatment waste	No cases
Total volume Vit (204,400 m3 x 0.4)	81,760 m3
Average volume / month (w/337 months)	243 m3 / month

F.3.3 Characteristics of Steam Reformed Case 2 Mineral Wasteform and Secondary Wastes

Steam Reforming (Case 2) and the Steam Reforming (Case 2) mineral WF are detailed in Section 4.3. The specific characteristics important for using the Feed Vector to characterize the steam reformed WF for disposal are presented in Table F-5.

Table F-5 Characteristics of Steam Reforming Case 2 WF – Granular Mineral

Volume change caused by steam reforming	1.2 (increases volume & decreases specific activities)
Density of final WF	800 kg/m3 (50 lb/ft3)
Solid Secondary wastes	detailed in F.5.4.4 Classifying Secondary WFs
Pretreatment wastes	No cases
Total volume (204,400 m3 x 1.2)	245,300 m3
Average volume (total/337 months)	728 m3 / month

F.3.4 Characteristics of Grout Case 2 Wasteform and Secondary Wastes

Grouting and the grouted WF (Grout Case 2) are detailed in Section 4.4. The specific characteristics important for using the Feed Vector to characterize the grouted WF for disposal are presented in Table F-6.

Table F-6 Characteristics of Grouted Wasteform (Grout Case 2)

Volume change caused by grouting	1.8 (increases volume & decreases specific activities)
Density of final WF	1770 kg/m3 (110 lb/ft3) (0.0624 lb./ft per kg/m3)
Solid secondary wastes	detailed in F.5.4.4 Classifying Secondary WFs
Pretreatment wastes	Yes, for 2e2 would create a PW for disposal at WCS, this is described in F.5.4.4
Total volume (204,400 m3 x 1.8)	367,900 m3

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[88] Based on six metric tons in 562 gallons

Average volume (total/337 months)	1092 m3 / month

The characteristics of the immobilized WFs and information in the Feed Vector are used together to assess the ability of each WF form to meet the waste acceptance criteria at the two disposal facilities.

F.4 INTEGRATED DISPOSAL FACILITY

F.4.1 General Description

Located in the 200 East Area of Hanford, the DOE is developing the IDF to provide a disposal facility for LLW and mixed-LLW including the Immobilized Low Activity Waste from the WTP, SLAW, and other related secondary wastes and IDF operational wastes. The first phase of construction of the IDF is complete and awaiting final DOE authorization to receive wastes at the facility.

F.4.1.1 Physical Setting

The IDF is located southwest of the WTP on the central plateau of Hanford, with approximately 380 feet of unconsolidated sands and gravels underlying the facility, and approximately 300 feet from the bottom of the IDF to the unconfined aquifer.

The stratigraphy consists of the Hanford formation and Ringold Formation. Surficial sediments are predominantly eolian, reworked Hanford sand and silt deposits. The Hanford formation is as much as 116 m (380 ft) thick at the IDF, reaching its greatest thickness along a NW-SE trending trough under the eastern part of the IDF site.[89] In general, the Hanford formation consists of poorly sorted, pebble to cobble gravel and fine- to coarse-grained sand, with lesser amounts of silt and clay lenses. The Ringold Formation reaches a maximum thickness of 285 ft (87 m) on the west side of the IDF site, thinning eastward. The Ringold Formation consists of layers of fluvial gravel sediments.

A NW-SE trending erosional channel is centered along the northeast portion of the site. The deepest portion is below the northern portion of the IDF site. This channel is a smaller part of a much larger trough the underlies the 200 East Area that resulted from scouring by floods (see Figure F-1).

F.4.1.2 Disposal Facility Design

The IDF currently consists of two disposal cells with a total capacity of approximately 300,000 m^3 and can be expanded as needed to a total capacity of approximately 900,000 m^3. The first two cells of the IDF were constructed in 2006 as shown in Figure F-2. The IDF includes engineered design features that contribute to the overall safety and performance of the facility and limit release of key contaminants to the environment. These features are highlighted in Figure F-3, and consist of 1) a modified Resource Conservation and Recovery Act (RCRA) Subtitle C barrier above the waste to limit water and bio-intrusion into the waste, and gaseous releases from the facility, 2) waste containers placed around the wasteforms for structural support and to limit water from contacting the waste during operations, and 3) liner and leak detection system with secondary containment to limit any water collected during operations and post-closure institutional control from entering the natural system beneath the IDF. A high point down the center of the liner system ensures the leachate from Cell 1 (right - west) does not contaminate the leachate from Cell 2 (left – east). The two separate leachate collection tanks are shown in the foreground of the photograph in Figure F-2. Cell 1 is for radioactive MLLW that contains dangerous or hazardous waste and is regulated under RCRA[90]; Cell 2 is for radioactive only low-level

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[89] Reidel, S.P. and K.R. Fecht. 2005. Geology of the Integrated Disposal Facility Trench. PNNL-15237. Pacific Northwest National Laboratory, Richland, Washington.

[90] Ecology. 2012. Hanford Dangerous Waste Permit, Rev. 8c. WA7 89000 8967, Part III Operating Unit Group 11, Integrated Disposal Facility Section III.11.C.5, Waste Acceptance Criteria and Waste Verification Requirements

waste that is regulated by DOE. Cell 1 is permitted by Washington State Department of Ecology and is identified as Unit 11, under the Hanford Site Wide RCRA Permit, Cell 2 is regulated under DOE O 435.1.[91]

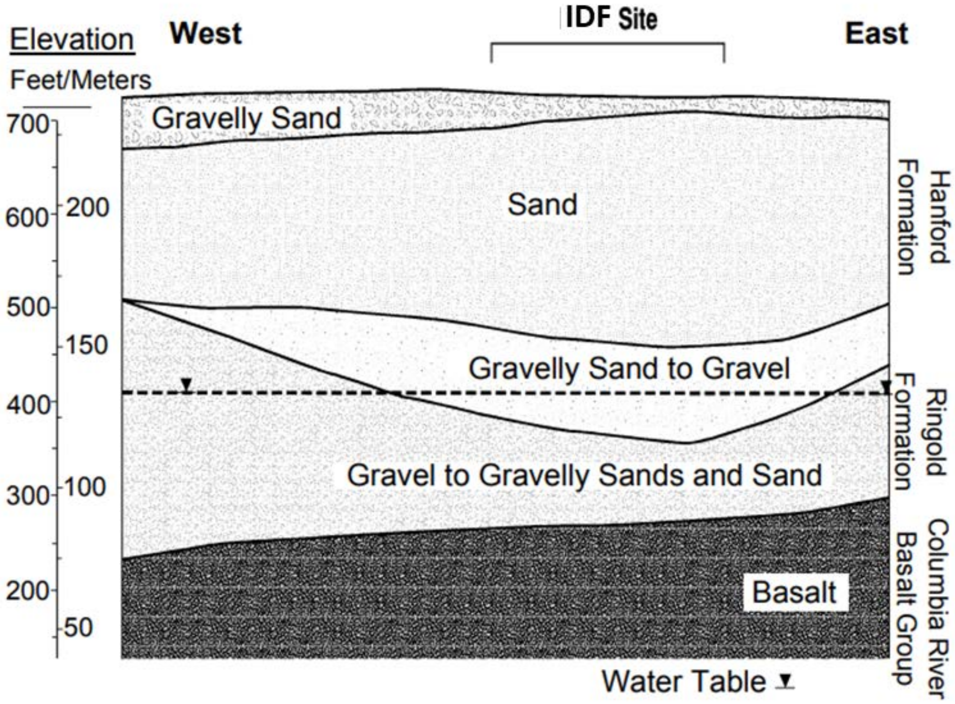


Figure F-1 West to east cross-section of the IDF site geology (Mann et al., 2001).

(https://fortress.wa.gov/ecy/nwp/permitting/hdwp/Rev/9/OU/IDF.html)

[91] Efforts are ongoing to modify the RCRA permit to allow all Hanford Site RCRA wastes to be disposed at IDF, and allow both Cell 1 and Cell 2 to be permitted for MLLW.

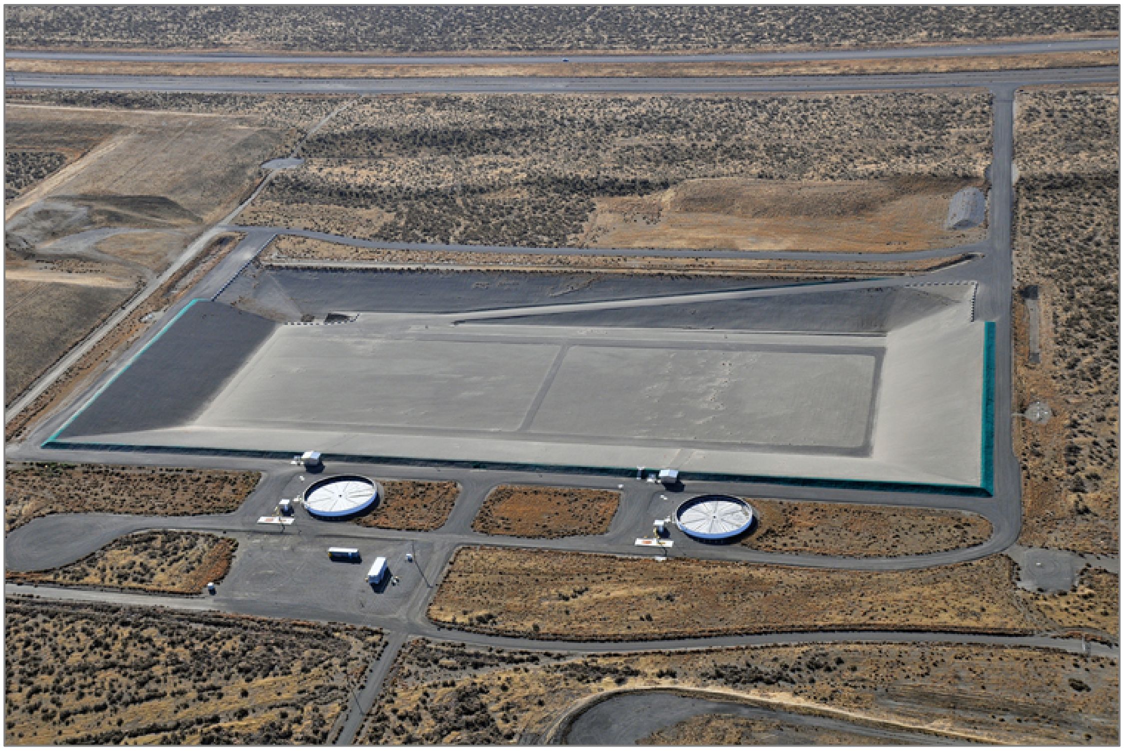
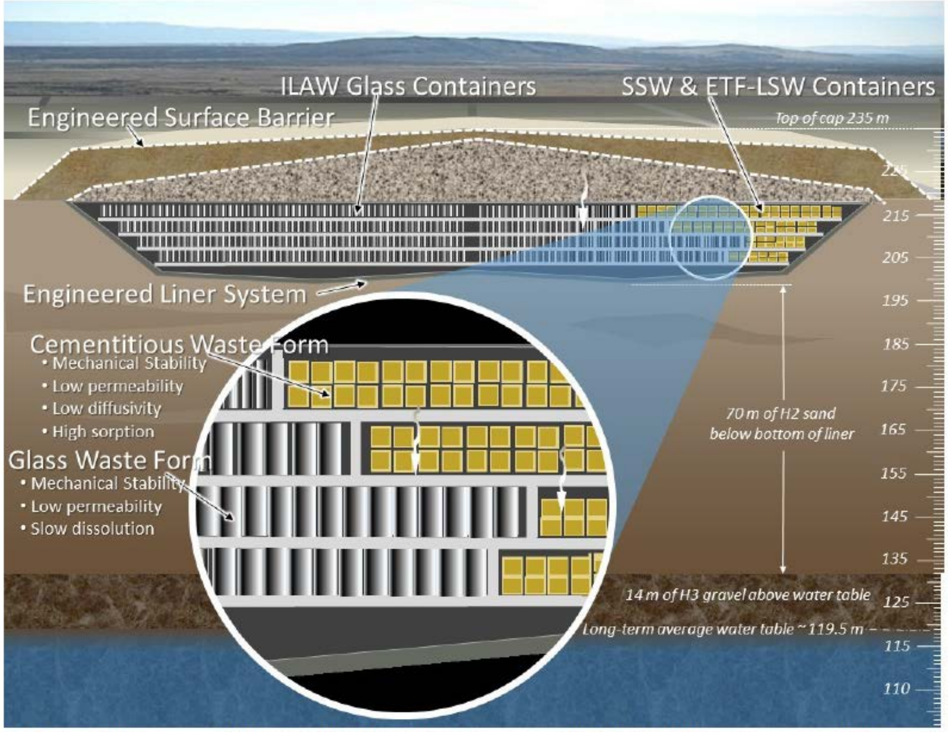


Figure F-2 Aerial View of the Two IDF Cells in the Hanford Site 200-East Area Southwest of WTP (a high point down the center of the liner system separates the two cells).



ETF = Effluent Treatment Facility ILAW = immobilized low-activity waste LSW = liquid secondary waste SSW = secondary solid waste

Figure F-3 Schematic Depiction of Engineered Safety Features of the IDF

F.4.2 Key Regulatory Requirements

For purposes of this analysis, only disposal in the RCRA permitted portion of the IDF is considered. The current IDF waste acceptance criteria (WAC) are documented within the RCRA dangerous waste permit (Ecology 2012). However, a final approved WAC has not yet been established. The current permit limits disposal at IDF to ILAW vitrified (glass) wasteforms from WTP and a glass wasteform from a previously proposed demonstration bulk vitrification system. Disposal in IDF must meet DOE O 435.1, *Radioactive Waste Management* requirements for waste incidental to reprocessing (WIR) that specify how tank wastes that have been managed as HLW are accepted for management as LLW. In addition, DOE O 435.1 requirements for near-surface disposal of LLW must be met. The LLW requirements are substantially addressed through a DOE Performance Assessment (PA) that evaluates the long-term impact of near-surface disposal through computer modeling analysis, to provide DOE with a reasonable expectation that LLW and MLLW disposal will meet the radiological performance objectives documented in DOE O 435.1 and its *associated Radioactive Waste Management Manual* (DOE M 435.2). In addition, the PA contains analyses that can be used to address operating conditions or requirements specified in the RCRA permit for the disposal facility. A draft 2017 performance assessment for IDF was recently completed and is awaiting public release. Previously, DOE issued an initial ILAW PA in 1998,[92] which was conditionally approved by DOE in 1999, and an update was issued in 2001.[93] A subsequent PA update in 2005 was deferred until after the completion of the Tank Closure and Waste Management EIS (TC&WM EIS) and record of decision was finalized. In addition to the PAs, two risk assessments were issued in 2003. One provided an update to the 2001 PA, incorporating the conceptual design for the IDF (Mann et al. 2003a. RPP-15834). The second looked at alternative wasteforms for supplemental immobilization of Hanford LAW (Mann et al. 2003b. RPP-17675).

F.4.2.1 RCRA Permit and WAC

Washington State Department of Ecology (Ecology) recently issued Revision 8c of the Hanford site-wide dangerous waste permit, including Operating Unit Group 11 for the IDF. (Ecology 2012). The IDF permit conditions specifically address general waste management, waste analysis and waste acceptance, recordkeeping and reporting, security, preparedness and prevention, contingency planning, inspections, personnel training, closure and post-closure requirements, and groundwater monitoring. Currently, the IDF permit restricts disposal operations and maintenance to ILAW from WTP, ILAW from the demonstration bulk vitrification system, and IDF operational wastes. Although the IDF PA addresses secondary wastes from ILAW glass processing, secondary waste disposal is not currently authorized by the IDF permit.

The waste analysis/waste acceptance conditions documented in the IDF permit identify specific analysis, documentation, and actions required by Ecology to dispose of waste in IDF[94]. This includes specific wasteform performance data, performance assessment results, and a requirement to perform additional model runs if requested by Ecology. The permit also requires creation and maintenance of an IDF modeling Risk Budget Tool that models the future impacts of the planned IDF wasteforms to underlying vadose zone and ground water, and compares results to various performance standards including drinking water standards. If modeling analyses project impacts within 75% of a performance standard, then the permit requires DOE and Ecology to meet to discuss mitigation measures or modified WAC for specific wasteforms. Further, the permit restricts disposal of any waste that “will result in a violation of any state or federal regulatory limit, specifically including but not limited to drinking water standards for any constituent as defined in 40 CFR 141 and 40 CFR 143.”

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[92] Mann et al, 1998. Hanford Immobilized Low-Activity Tank Waste Performance Assessment. DOE/RL-97-69, Rev. 0, U.S. Department of Energy, Richland, Washington.

[93] Mann et al, 2001. Hanford Immobilized Low-Activity Waste Performance Assessment: 2001 Version. DOE/ORP-2000-24, Rev. 0. U.S. Department of Energy, Richland, Washington.

[94] IDF Permit (WA7 89000 8967), Section III.11.C: Waste Analysis/Waste Acceptance.

Other waste acceptance criteria for the IDF include:

- Wastes must be compliant with RCRA Land Disposal Restrictions (LDR) (40-CFR-268)
- Prohibit Transuranic wastes
- Need to treat wastes that have the Waste codes D001 (ignitable), D002 (corrosive), D003 (reactive) (40-CFR-261) prior to disposal so that the resultant waste no longer exhibits these characteristics (Under the WTP Permit, these three waste codes must be removed before the waste is sent to the WTP)
- Free liquids must be <1% by weight volume
- Pre-waste acceptance required; waste pedigree needs to be verified by IDF
- There are maximum void space requirements for containers (i.e., must be >90% full).

Presently, there are no onsite treatment capabilities planned for the IDF. If additional treatment is required for a given waste stream, the waste will likely be sent to an approved offsite treatment facility. By regulation, the IDF should be able to accept solids with no additional treatment if they do not designate as dangerous/hazardous waste.

F.4.3 Disposal Performance Evaluation

Assessment of the projected performance of disposed wastes in the IDF has been the subject of several previous studies, including the 1998 and 2001 performance assessments[2,3] and the 2003 ILAW Risk Assessment that focused principally on disposal of ILAW glass[95], the risk assessments that focused on expansion of the wasteforms to be considered for disposal in the IDF to include secondary wastes and SLAW wasteforms,[96,97] and the Tank Closure and Waste Management EIS[98] and resulting ROD. The 2017 IDF performance assessment provides the most current formal evaluation of the projected performance of disposed wastes in the IDF, consistent with the requirements of DOE O 435.1 and DOE policy direction[99]. This evaluation includes comparison of differences and similarities between the modeling approaches, models, and parameters used in the TC&WM EIS with those used in the 2017 IDF PA. A summary of key differences relevant to this study are provided in the following sections.

F.4.3.1 2017 IDF Performance Assessment

The IDF PA addresses DOE requirements that the results of the analysis provide reasonable expectation that the facility will not exceed the performance objectives for a period of 1,000 years following closure of the facility. In addition, the PA analysis provides results that can be used to address operating conditions that are specified in the RCRA permit for IDF, including groundwater protection standards. Table F-7 identifies key analysis requirements, expectations, and assumptions used in the 2017 IDF PA.

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[95] The IDF was originally planned only for disposal of immobilized low-activity tank waste and was referred to as the ILAW disposal facility. The first performance assessments focused on ILAW glass disposal only. The two risk assessments performed in the early 2000's supported decisions to expand the mission of the ILAW disposal facility to additional LLW and MLLW and consider SLAW forms.

[96] Mann et al., 2003. Integrated Disposal Facility Risk Assessment. RPP-15834, Rev. 0, CH2MHILL Hanford Group, Inc. Richland, Washington.

[97] Mann et al., 2003. Risk Assessment Supporting the Decision on the Initial Selection of Supplemental ILAW Technologies. RPP-17675, Rev. 0, CH2MHILL Hanford Group, Inc., Richland, Washington.

[98] DOE. 2012. Tank Closure and Waste Management Environmental Impact Statement. DOE/EIS-0391. U.S. Department of Energy, Richland, Washington.

[99] The 2017 IDF PA explicitly addresses DOE HQ policy direction to DOE-RL and DOE-ORP titled "Modeling to Support Regulatory Decisionmaking at Hanford" (Internal memorandum 1301789) to maintain traceability to the prior NEPA analysis, especially the TC&WM EIS, including building upon the modeling tools and assumptions used by the TC&WM EIS.

Although the 2017 IDF PA has not been publicly released, the NAS Committee and Study Team received a public briefing and overview of the PA results.[100] The Team was also provided a copy of the draft report, and modeling input and output files to support this study. Summary of PA assumptions, inputs, and results documented in this report are based on pre-publication documentation provided to the Team, which may change in the final publicly released documents.

Table F-7 2017 IDF PA Key Analysis Assumptions and Requirements

Analysis Assumptions	**Requirement (R) or Expectation (E)**	**2017 IDF PA Analysis**
DOE Time of Compliance	1,000 years after facility closure (R)	Compliance period = 2051-3051
Extended time post-compliance period	1,000 – 10,000 years after facility closure (E)	Post Compliance Period = 3051-12051
Peak impacts	Extended run to assess peaks (E)	500,000 years
Points of Compliance 1. Groundwater pathway 2. Air Pathway 3. Inadvertent Intruder	1. 100-m buffer zone surrounding disposed waste (R) 2. Closest offsite receptor (R)	1. Highest concentration 100 m from edge of excavation 2. 20,000 m east-southeast of IDF (within first 100 years after closure only)
Period of Institutional Control	100 years (E)	Assumed leachate collection and leak detection are operable. No public individual resides within buffer zone
Performance Objective and/or Measure 1. All Pathways[1] 2. Atmospheric[1,2,3] 3. Acute Inadvertent Intruder[1] 4. Chronic Inadvertent Intruder[1] 5. Groundwater Protection[4]	1. 25 mrem/yr (R) 2. 10 mrem/yr & 20 pCi m^{-2} s^{-1} radon flux at surface (R) 3. 500 mrem (R) 4. 100 mrem/yr (R) 5. ≤4 mrem/yr beta-gamma dose equivalent (R) ≤15 pCi/L gross alpha activity (R) ≤5 pCi/L combined Ra-226 and Ra-228 (R) ≤30 µg/L Uranium (R) ≤8 pCi/L Sr-90 (R) ≤20,000 pCi/L H-3 (R)	

[1] DOE M 435.1-1 Chg 1

[2] 40 CFR 61, Subpart H (10 mrem/yr standard)

[3] 40 CFR 61, Subpart Q (20 pCi m^{-2} s^{-1} radon flux standard)

[4] 40 CFR 141

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[100] Lee, P. 2018. Overview of the 2017 IDF Performance Assessment for LAW. Presented to the NAS Committee on Supplemental Treatment of Low-Activity Waste at the Hanford Site, Washington, on February 28, 2018.

The development of a durable waste package (including the wasteform and the surrounding container barriers) is needed to ensure the long-term stability of materials and the isolation of radioactivity within the engineered IDF. This is accomplished by immobilizing the radioactive materials into wasteforms that provide physical, chemical and thermal barriers inhibiting radionuclide release. Wasteforms in the IDF must also be able to sustain the weight of the stacked wasteform packages and of soil overburden and potential intrusion. Resistance to leaching, fracturing and other modes of degradation are key characteristics that minimize wasteform degradation and radionuclide release when contacted with water. The environmental rationale for stabilizing the waste for near surface disposal is evident from specific TC&WM EIS analysis. Of the numerous radionuclides present in the Hanford tank waste, due to chemical and physical separations processes used in preparing the LAW, only Tc-99 and I-129 are expected in to be in the LAW in appreciable quantities. Only a small fraction of the total tank waste inventory for these constituents are projected to ultimately report to IHLW glass for offsite geologic disposal. Therefore, one can look to the no action alternative in the TC&WM EIS to gain insight on the projected environmental impacts if the LAW stream was left untreated, and/or disposed directly in lieu of stabilization in robust wasteform. For example, Figure 5-10 of the TC&WM EIS is reproduced below in Figure F-4 of this appendix, and reflects the environmental consequences of tank closure alternative 1, which assumes the, WTP construction is halted, the tank waste is left in the existing DSTs and SSTs, the core zone and tanks are maintained under institutional control for 100 years, and then tanks are left to degrade and release to the environment. For Tc-99, impacts to groundwater beneath the 200 Area plateau peak around year 3900 at groundwater concentrations approximately 2 to 2.7× MCLs are identified as the “benchmark concentration” in the figures. Figure 5-21 of the TC&WM EIS (not shown) also depicts the spatial groundwater concentration of Tc-99 at approximately the peak impact time, with large areas of groundwater plumes within the current boundary of the Hanford site extending from the core zone (plateau) to the Columbia River at concentrations exceeding the MCL.

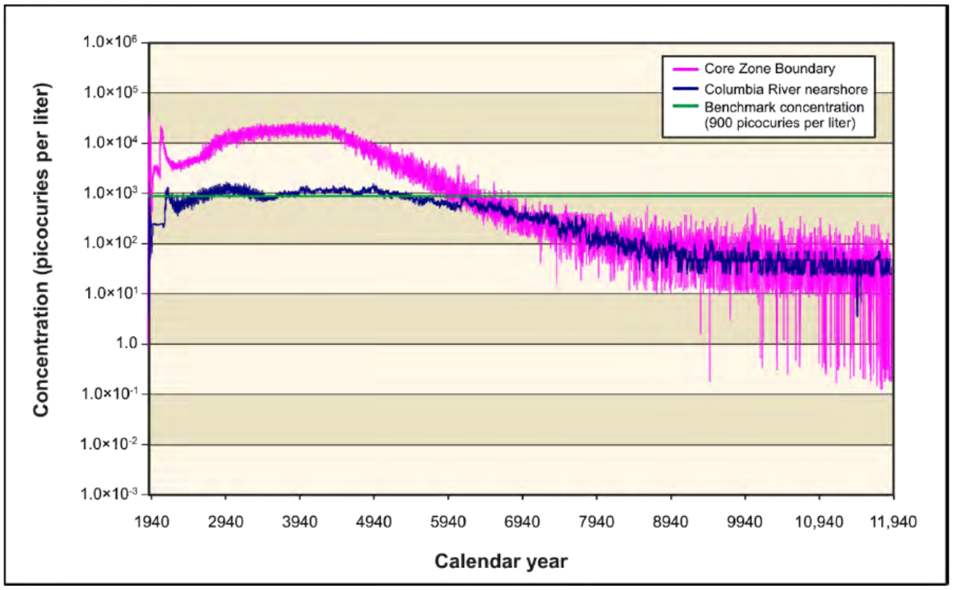

Figure 5–10. Tank Closure Alternative 1 Technetium-99 Concentration Versus Time

Figure F-4 Impacts to Groundwater of Untreated Tank Waste from the TC&WM EIS, No Action Alternative.

The 2017 IDF PA considered two potential wasteform releases from LAW processing: 1) ILAW and SLAW glass[101] and 2) non-glass (cementitious) secondary wasteforms. Glass, as the end-product of waste vitrification, is

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[101] The 2017 IDF PA refers to all immobilized LAW as ILAW glass and does not use the term “SLAW.” The 2017 IDF PA assumes an expansion of the current LAW vitrification capabilities to produce ILAW glass from the total feed inventory of

considered a more stable wasteform relative to cement-based wasteforms. However, vitrification does generate secondary wastes that must be further stabilized to be disposed in IDF, and these are currently assumed to be grouted. For silicate-based glass and mineral forms, the 2017 IDF PA modeled the potential release using geochemical modeling, representing rate-controlling mechanisms where the glass wasteform slowly dissolves over time and contaminants are released. For cementitious wasteforms, a physical model of contaminant diffusion was used in the PA. Empirical effective diffusion coefficients were measured in short-term laboratory experiments to model the long-term performance of the cementitious wasteforms. Release models were used to estimate radionuclide release, which were then considered as source terms for a vadose zone fate and transport model.

The primary wasteforms from LAW processing that were analyzed in the 2017 IDF PA included:

- The primary ILAW Glass wasteform (ILAW Glass) generated from vitrification of the total LAW feed stream. The ILAW glass is projected in the PA to contain the majority of ^{99}Tc and ^{129}I.
- Liquid secondary wastes (LSW) generated from the vitrification offgas scrubber and condensates that ultimately are sent to the Effluent Treatment Facility, dried to a granular/powder residue, and solidified in a cementitious/grout matrix. The LSW is projected to contain very low levels of both ^{99}Tc and ^{129}I.
- Solid secondary waste (SSW), including granular activated carbon (GAC) and HEPA filters that are part of the LAW vitrification offgas treatment system, and are to be solidified in a cementitious/grout matrix. The SSW is projected to contain both ^{99}Tc and ^{129}I.
- Solid secondary wastes resulting from other treatment processes such as the WTP pretreatment facility or HLW vitrification facility were also analyzed in the IDF PA. However, these wastes are not associated directly with LAW processing and are therefore not discussed or considered further in this study.

Key Results from the 2017 IDF PA relevant to this study are as follows:

- No performance objectives or measures were exceeded within the 1,000-year DOE compliance period. The highest calculated dose projected was for the chronic inadvertent intruder scenario where interception of four ILAW glass cylinders occurs from well drilling at the end of the institutional control period. In this case the dose is <50% of the 100 mrem/yr maximum dose rate performance objective.
- For the air and groundwater exposure pathways, the predicted dose during the DOE compliance period, is dominated by the air pathway for gaseous radionuclides, but is a factor of 50 below the 10 mrem/yr performance objective.
- Only the groundwater protection measure (beta-gamma dose equivalent) is exceeded during the post-compliance period (>1000 years), where dose calculated using the U.S. EPA dosimetry method projects a dose rate of 4.9 mrem/yr (vs. ≤4 mrem/yr beta-gamma standard) resulting from ^{99}Tc and ^{129}I within solid secondary waste, specifically the grouted GAC and HEPA filters SSW
- Modeling revealed that ^{99}Tc and ^{129}I are the primary dose contributors, through the groundwater pathway, to a future member of the public in the 10,000 years that follow closure of the IDF. All other radionuclides are insignificant contributors to the total dose and extending simulations to 500,000 years revealed that the peak dose occurs within the first 10,000 years. After more than 200,000 years, ^{226}Ra becomes a dominant dose contributor, but less so than the earlier peak doses from ^{99}Tc and ^{129}I.

Relative to the scope of this study, the 2017 IDF PA does not consider alternative wasteforms beyond ILAW glass for SLAW, and the corresponding secondary wastes generated from ILAW glass production. Therefore, to address IDF wasteform performance of alternative SLAW wasteforms and any secondary wastes generated from SLAW processing, additional modeling and performance evaluation is necessary.

LAW, which is generally equivalent to the ILAW plus SLAW key radionuclide inventory documented in System Plan 8 and used in this study (see Table F-9).

F.4.3.2. SLAW Performance Evaluation Strategy and Approach

A general approach for evaluating wasteform behavior in a disposal site was initially developed nearly twenty years ago. This approach outlined logical steps to validate and confirm the corrosion behavior of materials whose life expectancies must greatly exceed the length of time over which experimental data can be obtained. The strategy identified here was to address evaluation of the alternative SLAW wasteforms and their secondary wastes was based on review of the 2017 IDF PA technical approach, results, and identification of advances in wasteform development and modeling that were not considered in prior SLAW analysis, such as the PA, TC&WM EIS, or 2003 Supplemental Immobilization Risk Assessment. Three technical needs for the performance evaluation emerged from this analysis:

1. ***Reactive transport methodology***. The 2017 IDF PA used a geochemical simulator and reactive transport code (STOMP) to quantify the release of contaminants from the glass wasteform. Explicit coupling of unsaturated flow, chemical reactions, and contaminant transport processes may be important for accurately quantifying contaminant release. For example, the ion activity product will vary spatially and temporally within the repository, and depends on system properties, such as flow rates, glass surface area, and alteration products formed as the wasteform undergoes dissolution. Because transport and chemical processes interact, a reactive chemical transport model is required to capture this near-field interaction, but only for those wasteforms where geochemistry is needed to describe the waste release.

   The strategy in this NDAA study is to also use a reactive transport approach to simulate glass wasteform degradation and the release and transport of radionuclides within the disposal facility. The eSTOMP simulator was used (Fang et al. 2015), the scalable version of STOMP (White et al. 2015), to evaluate contaminant release from the wasteforms, transport and feedback mechanisms through the engineered system, and transport through the vadose zone to the groundwater. Both STOMP and eSTOMP are managed as NQA-1 (ASME NQA-1-2008 and NQA-1a-2009) quality software and have undergone quality assurance testing and verification for use in these types of analyses.

2. ***Wasteform stacking scenarios within the facility***. The 2017 PA identified how stacking lifts of different wasteform containers could impact potential changes in vertical saturation distributions within the facility. Although impacts on wasteform dissolution rates were examined for like wasteforms using two vertically stacked lifts, a full stack of containers spanning the maximum height of the IDF was not simulated in the IDF PA. Potential interactions from the adjacent emplacement of different wasteforms was also not simulated in the PA, but separate studies have indicated potential impacts of intermingled wasteforms.

   The strategy in this NDAA study is to simulate a full stack (4) of lifts for each wasteform, allowing for up to eight containers (depending on the height of the waste package) to be represented in the simulation. Potential interactions from different intermingled wasteforms have not been addressed, as it is assumed that operational vs. wasteform release tradeoffs will be assessed in future performance assessments and that the IDF can accommodate separation of dissimilar wasteforms if necessary.

3. ***Wasteform systems.*** The 2017 IDF PA explicitly analyzed ILAW glass and cementitious secondary wasteforms, but did not consider advanced glasses, steam reforming product, SLAW grout and secondary wastes from these alternative non-glass SLAW treatment wasteforms. In addition, there has been advancement in understanding of both steam reforming product and SLAW grout wasteform performance since the last analysis was performed in the TC&WM EIS. Whereas a range of different inventories were used in the 2017 PA to explore uncertainty, the current SLAW feed vector represents a potentially different basis for contaminant distribution across primary and secondary wasteforms.

> The strategy in this NDAA study is to use the 2017 IDF PA results for those wasteforms where the PA represented the best current technical basis (i.e., ILAW glass and secondary waste), but also include an updated performance evaluation for other wasteforms. In addition to the LAWA44 glass used in the 2017 IDF PA, the updated performance evaluation included the ORLEC28 advanced glass. Steam reforming product and SLAW grout wasteforms were also included in the this updated assessment. Best available inventory information was also used in this study.

The primary objective of the NDAA wasteform disposal performance evaluation was to assess and compare the performance of the various SLAW wasteform options under consideration for disposal within the IDF, using the most current information available on contaminant inventory, wasteform mechanism of release, and wasteform performance. Wasteform performance is one of the most significant factors impacting risk to human health and the environment associated with exposure. The approach was to separately model near-field release and transport of key radionuclides (i.e., ^{99}Tc and ^{129}I) from each wasteform to obtain projected flux rates out of the IDF as a function of time. A unit release of each contaminant was assumed so that a fractional release rate from the IDF could be scaled based on the total inventory expected to be sequestered into each wasteform. The existing PA analysis and results were also used to equate the release from the total system of primary and secondary wasteforms for each SLAW processing option.

Three separate systems of secondary low-activity waste (SLAW) were simulated, each with a different mix of wasteforms based on inventory and feed vector estimates as shown in Table F-8. These wasteforms were considered to be part of the same system because pretreatment and LAW processing not only create a targeted wasteform (e.g., glass, SLAW grout or steam-reforming product), but also generate solid and liquid secondary wastes. As shown in the vitrification reference case above, the fabrication of the glass wasteform also results in secondary liquid and solid wastes that will be converted to stable solid wasteforms to be disposed of in the IDF.

Table F-8 Primary LAW and SLAW Wasteform Systems for IDF Evaluation

Analysis Case	**Primary LAW Wasteforms**		**SLAW Wasteforms**	
	LAW	**Secondary Wastes**	**SLAW**	**Secondary Wastes**
1. Vitrification Reference Case (2017 IDF PA)	ILAW Glass	LSW - ETF SSW - HEPA filters SSW - GAC sorbent	Glass	LSW - ETF SSW - HEPA filters SSW – GAC sorbent
2. Grouting			Cast Stone	SSW – HEPA filters SSW - GAC sorbent
3. Steam Reforming			FBSR Mineral - Macroencapsulated	SSW – HEPA filters SSW - GAC sorbent

For each LAW system evaluated, a contaminant-specific total effective flux to the environment is calculated by summing the wasteform-specific rates through the bottom of the disposal facility. Because release rates and performance may vary over time, estimates are evaluated over the time period from facility closure up to 10,000-years, consistent with the 2017 IDF PA. The fractional release rates from the IDF were then related to groundwater concentrations. This approach enabled direct comparison of the alternative SLAW options and systems of wasteforms to a regulatory metric – groundwater concentration at a point of compliance monitoring well 100 m downgradient from the facility.

A brief description of each of these three systems of wasteforms is provided below, along with a description of their inclusion in this study.

Case 1: Vitrification Reference Case. The baseline ILAW glass was assessed in the 2017 IDF PA, and further analysis, but the analysis did not include advanced glasses because characterization data were not available to parameterize wasteform behavior. However, glass compositions and dissolution rates have recently become available for advanced glass formulations. . This recent work in glass formulation and melter testing suggest that significant increases in waste loading for both high-level waste (HLW) and low-activity waste (LAW) glasses are possible over current system planning estimates. Glass simulations executed in this analysis included the following:

- A benchmark simulation of the LAWA44 baseline glass was executed to compare results with the 2017 IDF PA, which included the incongruent dissolution of 1) glass to its aqueous constituents and 2) glass to a hydrated glass, which was then subject to dissolution.
- LAWA44 baseline glass simulation that required the LAWA44 glass to be first hydrated, before undergoing dissolution. This update in simulating wasteform behavior is consistent with recent conceptualizations that anticipate hydration to occur first on the outside of the glass exposed to ambient pore water before undergoing dissolution.
- ORLEC28 advanced glass simulation that also required hydration to occur first before undergoing dissolution.

Processing of the SLAW feed vector will generate secondary wastes, including SSW from the offgas treatment systems such as HEPA filters and granular activated carbon (GAC) adsorption beds, and liquid secondary waste (LSW), including process condensates and scrubber/off gas treatment liquids from the thermal waste treatment processes. The products of both SSW and LSW are expected to be subsequently processed within a solidification treatment unit and stabilized in a grout/cement-based solid wasteform to be disposed of in the IDF. The following LSW and SSW simulations were executed:

LSW

- A benchmark simulation of the release of I-129 from grouted liquid secondary waste was executed to compare results with the 2017 IDF PA. Once results were verified, simulations using different parameter sets to describe diffusion and sorption (distribution coefficient) were executed, assuming the wasteform was placed in B25 containers.
- Release of Tc-99 from grouted liquid secondary waste was simulated using different parameter sets to describe diffusion and sorption (distribution coefficient), assuming the wasteform is placed in B25 containers. A benchmark simulation was not performed for this release.

SSW

- A benchmark simulation for the release of Tc-99 from HEPA encapsulated secondary wastes was executed to compare results with the 2017 IDF PA. Once results were verified, simulations using different parameter sets were executed, assuming the wasteform was placed in B25 containers.
- A benchmark simulation for the release of I-129 from GAC was executed to compare results with the 2017 IDF PA. Once results were verified, simulations using different parameter sets were executed, assuming the wasteform was placed in B25 containers.

Case 2: Grout. Development and testing of both grouted SLAW and secondary wastes from SLAW processing have been performed over the past 15 years. Some of this data supported the 2017 IDF PA analysis of grouted secondary waste, but not a grouted SLAW wasteform. New data and formulations for cementitious wasteforms from LAW waste streams are now available and include data on ^{99}Tc leach testing as a function of pH, the effective diffusivity for ^{99}Tc and ^{127}I, and desorption and solubility estimates for ^{99}Tc. Hence, no benchmark simulations could be executed for grouted SLAW waste, but the following simulations were executed:

- Release of Tc-99 from grouted (Cast Stone) waste was simulated using different parameter sets to describe diffusion and sorption (distribution coefficient), assuming the wasteform is placed in B25 containers. This release was *not* simulated in the 2017 PA.
- Release of I-129 from grouted (Cast Stone) waste was simulated using different parameter sets to describe diffusion and sorption (distribution coefficient), assuming the wasteform is placed in B25 containers. This release was *not* simulated in the 2017 PA.
- Release of I-129 from GAC (SSW) was simulated using different parameter sets, assuming the wasteform is placed in B25 containers.
- Release of I-129 from HEPA filters was simulated using different parameter sets, assuming the wasteform is placed in B25 containers.
- Release of Tc-99 from HEPA filters was simulated using different parameter sets, assuming the wasteform is placed in B25 containers. This release was *not* simulated in the 2017 PA.

Case 3: Steam Reforming. Steam reforming has been considered as an alternative technology for the immobilization of high-sodium-containing radioactive wastes and was evaluated in the risk assessment strategy carried out in 2003 (Mann et al, 2003, McGrail et al. 2003). With the addition of clay, aqueous LAW is converted to a granular, mineralized wasteform while converting organic components to CO_2 and steam, and nitrate/nitrite components, if any, to N_2. Prior analyses have presented a wide range of performance behavior for steam reforming product ((Bacon and McGrail 2005; TC&WM EIS 2012). Since then, additional characterization work has been performed but is still considered incomplete. Simulations executed in this analysis included the following:

- A reactive transport simulation was executed using the reaction network, mineral assemblage, and dissolution rates from McGrail et al. (2003). Since recent work identified a technetium containing sodalite phase, this mineral was also represented in the simulation, in addition to the nosean and nepheline minerals considered in Bacon and McGrail (2005).
- Simulations were executed that considered Tc-99 release based on the diffusion release approach used to represent contaminant releases from grouted wasteforms (e.g., SSW, LSW, etc.). This approach involves translating an effective diffusion coefficient measured under diffusion-only conditions, to equivalent diffusion and distribution coefficients relevant to advective-diffusive transport.

Solid secondary wastes also will be generated. The following simulations were also executed:

- Release of I-129 from GAC (SSW) was simulated using different parameter sets, assuming the wasteform is placed in B25 containers.
- Release of I-129 from HEPA filters was simulated using different parameter sets, assuming the wasteform is placed in B25 containers.
- Release of Tc-99 from HEPA filters was simulated using different parameter sets, assuming the wasteform is placed in B25 containers. This release was not simulated in the 2017 PA.

F.4.3.3. Comparison of Performance Evaluation Basis Between TC&WM EIS, IDF PA, and NDAA Study

Wasteform disposal performance evaluation of ILAW and SLAW wasteforms have been conducted previously, and differences in the analysis are principally associated with the following uncertainties, parameters, and assumptions:

1. Inventory of key contaminants projected for disposal in various wasteforms. Both the total inventory of key contaminants being processed, and the distribution (aka, split factors) of those radionuclides to different waste streams has varied over time.
2. Wasteform performance parameters, understanding, and assumptions about contaminant release and distribution
3. Assumptions regarding the IDF engineered system, including surface barrier and liner longevity and degradation, and infiltration.

The following discussion summarizes the key similarities and differences between the prior EIS, current IDF PA, and this Study in each of these three areas.

Inventory and Distribution

The Hanford tank waste inventory, formally documented as the “Best Basis Inventory (BBI)” is updated on a regular basis as a result of updated tank characterization data, data analysis/assessment, and waste management activities. The BBI has evolved over time, and in the case of the TC&WMEIS, 2017 IDF PA, and the current integrated flowsheet System Plan 8 feed vector, all three studies are based on different BBI bases.

In addition to the BBI starting inventory, understanding of and updates to the technical basis for the waste processing flowsheet has resulted in an evolving basis for where key contaminants will report within the flowsheet, including split factors that describe the overall flow or material balance of key constituents to solid, liquid, and vapor streams as they pass thru critical unit operations in the processing facilities.

Table F-9 summarizes the key inventory and distribution differences. A significant decrease (39%) in the BBI for I-129 occurred between 2002 (TC&WM EIS basis inventory) and 2014 (2017 IDF PA base case basis inventory), which is described in detail in the 2017 IDF PA and supporting documents. In addition, significant changes in the basis for distribution of key contaminants occurred during this time, as the WTP flowsheet, testing, design, and construction progressed. The IDF PA analysis represents current expectation that the WTP will process a larger fraction of the LAW, and higher inventory of CoCs than assumed in the TC&WM EIS, leaving a smaller fraction to process through SLAW. While uncertainty still exists in the ultimate distribution of key CoCs, the current basis for reporting of CoCs to primary wasteform and secondary wasteforms has substantially changed from that of the TC&WM EIS.

For this study, the feed vector as defined in the integrated flowsheet (System Plan 8, Base Case) and based on the 2016 BBI is slightly lower than the IDF PA inventory basis. However, while the inlet BBI inventories are similar, the split factors captured in the detailed integrated flowsheet are substantially different and less conservative than those used in the IDF PA. Therefore, for this study, the BBI feed vector inventory is used, but split factors are applied for the glass only case based on the more conservative 2017 IDF PA basis. This provides for better comparison to the current IDF analysis.

Table F-9 Comparison of Tc- 99 and I-129 Inventories in TC&WM EIS, 2017 IDF PA, and System Plan 8 Integrated Flowsheet Used in this Study

	TC&WM EIS		**2017 IDF PA**		**Integrated Flowsheet (System Plan 8, Base Case)**	
Wasteforms	**Tc-99 (Ci)**	**I-129 (Ci)**	**Tc-99 (Ci)**	**I-129 (Ci)**	**Tc-99 (Ci)**	**I-129 (Ci)**
IHLW Glass	382	0.39	-	-	1,530	0.53
ILAW Glass	28,800	9.56	26,400	16.5	12,227	15.0
SLAW Glass or Alternative					11,593	10.5
ETF-LSW	86.3	33.6	0.23	0.064	0.26	0.023
SSW	431	4.65	20.0	12.1	ND[1]	ND
LAW Melter	Included in LAW Glass	Included in LAW Glass	37.5	<1		
Total Tank Inventory – Best Basis	29,700	48.2	26,500	29.4	25,334	28.7

[1] ND – Not Determined

Wasteform Performance

Similar to inventory, wasteform performance information and technical basis has evolved over time. The TC&WM EIS relied substantially on data packages produced shortly after the 2003 risk assessment and wasteform testing studies, including a single glass dissolution fractional release rate originating from reactive transport simulations in 2001 and 2003 on a benchmark ILAW glass at that time. The 2017 IDF PA used more recent studies of three standard WTP ILAW glasses, benchmarking fractional release rates for these glasses against earlier ILAW glass simulations.

For grouted wasteforms, all studies have assumed a diffusion-controlled release from grouted wasteforms. For SLAW grout, the TC&WM EIS used effective diffusion coefficients in a similar range (10^{-8} to 10^{-10} cm^2/s) as that used in the original 2003 risk assessment based on limited laboratory studies. The 2017 IDF PA did not analyze an SLAW grout case. The grouted secondary waste effective diffusion coefficients were based on recent secondary waste laboratory studies, and a range of waste- and waste-form-specific diffusion and distribution coefficients. The TC&WM EIS used the same effective diffusion coefficients for both SLAW grout and grouted secondary wastes. This study is using a range of effective diffusion coefficients based on the most recent SLAW grout laboratory testing, along with the IDF PA basis for grouted secondary waste.

For steam reforming product, the TC&WM EIS acknowledged the limits of then current data (2003-2005) on the FBSR mineral product, and used an upper-limit solubility estimate for a single mineral from a geochemical model. The IDF PA did not analyze any SLAW steam reforming case. The NDAA study is relying on updated information describing the minerals, distribution of CoCs into those minerals, updated mineral characterization literature to model the dissolution of the sodalite minerals with a reactive transport code.

IDF Engineered System

The IDF engineered system assumptions in the EIS, IDF PA, and this study are generally consistent. The surface cap is assumed to limit infiltration to 0.5 mm/yr during its 500-year service life, at which point is assumed to degrade. The EIS assumed degradation to 0.9 mm/yr infiltration after 500 years, and then analyzed a sensitivity case with 3.5 mm/yr infiltration. The IDF PA used the EIS sensitivity case as the base assumption for degradation at 500-years, consistent with a recent Waste Management Area C PA. This study is using the same IDF PA assumptions for consistency, which also includes degradation/failure of the leachate collection system at 500-years. Unlike the EIS, the PA considers catastrophic failure of the liner unlikely, therefore locally-increased recharge to the vadose zone under the liner (i.e., leachate collection low points) is included in the PA.

F.4.3.4. Disposal Performance Evaluation Simulations

In a comprehensive performance assessment, resources and time allow for a range of simulations including sensitivity analyses and probabilistic analysis to assess the uncertainty associated with the performance estimates. Gives the limited time and resources available for this study, the team emphasized analysis of available data and subjective judgment to quantify uncertainty when relevant data were absent or incomplete. As a result, bounding estimates were used to represent a reasonable range of wasteform release parameters, creating subjective confidence intervals that should reasonably bound IDF disposal performance for each alternative Key uncertainties in these range of parameters are discussed for each alternative.

Simulations were executed to quantify the wasteform dissolution and/or contaminant release from each primary and secondary wasteform, in order to estimate flux of the key radiological contaminants of concern impacting the IDF performance—^{99}Tc and ^{129}I. These simulations are briefly described below.

Benchmarking

Simulation benchmarking involves the comparison of model output given similar inputs. For this analysis, benchmark simulations were executed for comparison to select 2017 IDF PA near-field wasteform degradation simulations. The benchmark simulations were executed for those wasteforms in which the most current performance data was available and used in the 2017 PA to describe dissolution behavior within the IDF facility, and using the two wasteform stack scenarios executed in the 2017 IDF PA. Benchmark simulations were executed for ILAW glass, LSW and SSW forms, using STOMP input files provided by the tank operations contractor to assure that the benchmarking directly mirrored the PA simulations, to build model confidence for simulations supplementing the 2017 IDF PA analyses. This also provides confidence in the use of eSTOMP, the parallel version of the STOMP simulator, which allowed for much faster execution times. Release and dissolution rates used in these benchmark studies were based on laboratory measurements that were documented in data package reports (Flach, et al. 2016, Cantrell, et al. 2016) that fed the PA analysis and were used in the 2017 PA calculations:

1. The benchmark simulation for glass uses a reactive transport simulation approach, using a dissolution rate law based on transition state theory. The redox environment is determined by geochemical reactions that are simulated within the disposal facility. No new data are available for describing glass dissolution within the IDF.
2. The benchmark simulation for SSW represents wasteform degradation within an oxidized environment, using a diffusive-advective transport approach that represents geochemical interactions with a linear distribution coefficient (K_d) used to describe geochemical interactions that retard diffusion out of the wasteform.
3. The benchmark simulation for LSW represents wasteform degradation within an oxidized environment, using a diffusive-advective transport approach that represents geochemical interactions with a linear distribution coefficient (K_d) used to describe geochemical interactions that retard diffusion out of the wasteform.

Tables F-10 through F-12 list key parameters used in the 2017 PA simulation scenarios for glass, LSW, and SSW. Simulations included in this analysis are indicated with an asterisk in these tables. Note that the secondary wasteform releases are described with both a diffusion coefficient and distribution coefficient (K_d), except for the HEPA simulation which is described with an effective diffusion coefficient.

Table F-10 2017 IDF PA Rate Law Parameters for LAWA44 Glass at 15°C (Pierce et al. 2004)

$\vec{k}_0$		K_g(a)	η	E_a	σ	r_{IEX}
Reported Forward Rate Constant (g/[m^2 d])	Converted(b) Forward Rate Constant (mol/[m^2 s])	Glass Apparent Equilibrium Constant Based on Activity Product *a*[SiO_2(aq)]	pH Power Law Coefficient	Glass Dissolution Activation Energy (kJ/mol)	Temkin Coefficient	Na Ion-Exchange Rate (mol/[m^2 s])
1.3×10^4	2.2×10^{-3}	1.87×10^{-3}	0.49 ±0.08	60 ±7	1	5.3×10^{-11}

Table F-11 Solid Secondary Waste Parameters used in 2017 IDF PA

Secondary Waste Material	Contaminant Of Concern	Diffusion Coefficient (cm^2/s)	Distribution Coefficient (K_d) (mL/g)	Reference
Silver Mordenite*	Iodine	5.40E-08	502	IDF PA Table 5-28
Grouted Carbon Absorber/Granular Activated Carbon (GAC)*	Iodine	5.40E-08	302	IDF PA Table 5-28
Ion Exchange Resin	Iodine	5.40E-08	2	IDF PA Table 5-28
HEPA Filters	Iodine	2.9E-08	4	IDF PA Table 5-28
Ion Exchange Resin*	Technetium	5.40E-08	0.4	IDF PA Table 5-27
HEPA Filters*	Technetium	2.9E-08	0.8	IDF PA Table 5-27

*Executed as a benchmark simulation

Table F-12 Liquid Secondary Waste Parameters used in 2017 IDF PA

Contaminant Of Concern	Grout Formulation	Diffusion Coefficient (cm^2/s)	Distribution Coefficient, (K_d) Oxidizing (mL/g)	Distribution Coefficient, (K_d) Reducing(mL/g)	Reference
Iodine*	Hydrated Lime	1.6E-09	4		IDF PA Table 5-35
Iodine	Fly Ash	1.3E-09	4		IDF PA Table 5-35
Technetium	Hydrated Lime	1.6E-09	0.8		IDF PA Table 5-35
Technetium	Fly Ash	1.3E-09	0.8		IDF PA Table 5-35
Iodine	Hydrated Lime	1.6E-09		0	IDF PA Table 5-38
Iodine	Fly Ash	1.3E-09		0	IDF PA Table 5-38
Technetium	Hydrated Lime	4E-10		1000	IDF PA Table 5-38
Technetium	Fly Ash	2.9E-09		1000	IDF PA Table 5-38

*Executed as a benchmark simulation

In the 2017 IDF PA, two stacked wasteforms and two different types of wasteform boxes (B25 containers and 55 gallon drums) were simulated for LSW and SSW. Only a quarter of the wasteform containers were represented in the simulation domain, assuming an axis of symmetry in the x- and y-coordinate directions, as shown in Figure F-5. Only the B25 containers were used in this assessment.

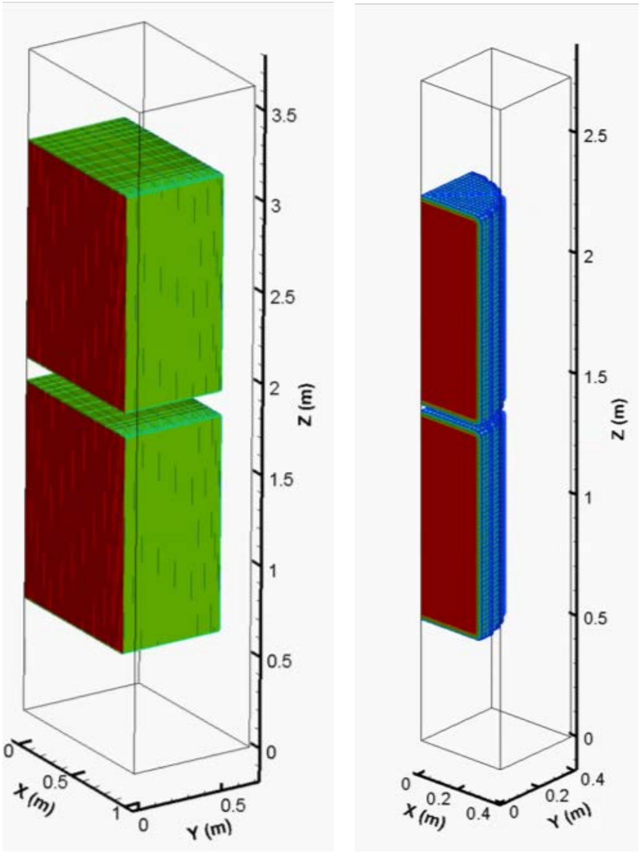

Figure F-5 Two container scenarios for the B-25 container (left) and the 55-gallon drum (right) for LSW and SSW simulations. Note only one quarter of the domain is simulated under an assumption of symmetry in the x- and y-coordinate directions.

The 2017 IDF PA represented the glass domain in two-dimensions as shown in Figure F-6. Similar to the LSW and SSW simulation domains, two wasteforms were represented but differ in size because the waste container dimensions differ.

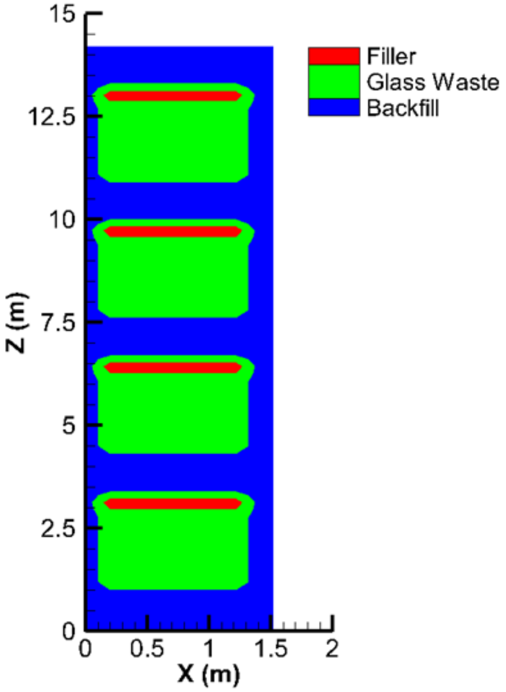

Figure F-6 2D simulation domain for the LAW glass simulation with four stacked waste packages

A comparison of STOMP and eSTOMP simulation results are shown in Figure F-7. This figure plots the solute flux that exits the IDF facility and would be readily available for transport to groundwater. Results between eSTOMP and STOMP are so closely aligned that the two lines appear as one. This is an expected result given that eSTOMP evolved from STOMP and shares the same input file. The primary difference is an added code base that allows eSTOMP to be executed on multiple processors, which significantly reduces simulation run times. In the benchmark simulations shown in Figure F-7, eSTOMP was executed on 24 cores and executed up to 24 times faster than the serial STOMP simulations.

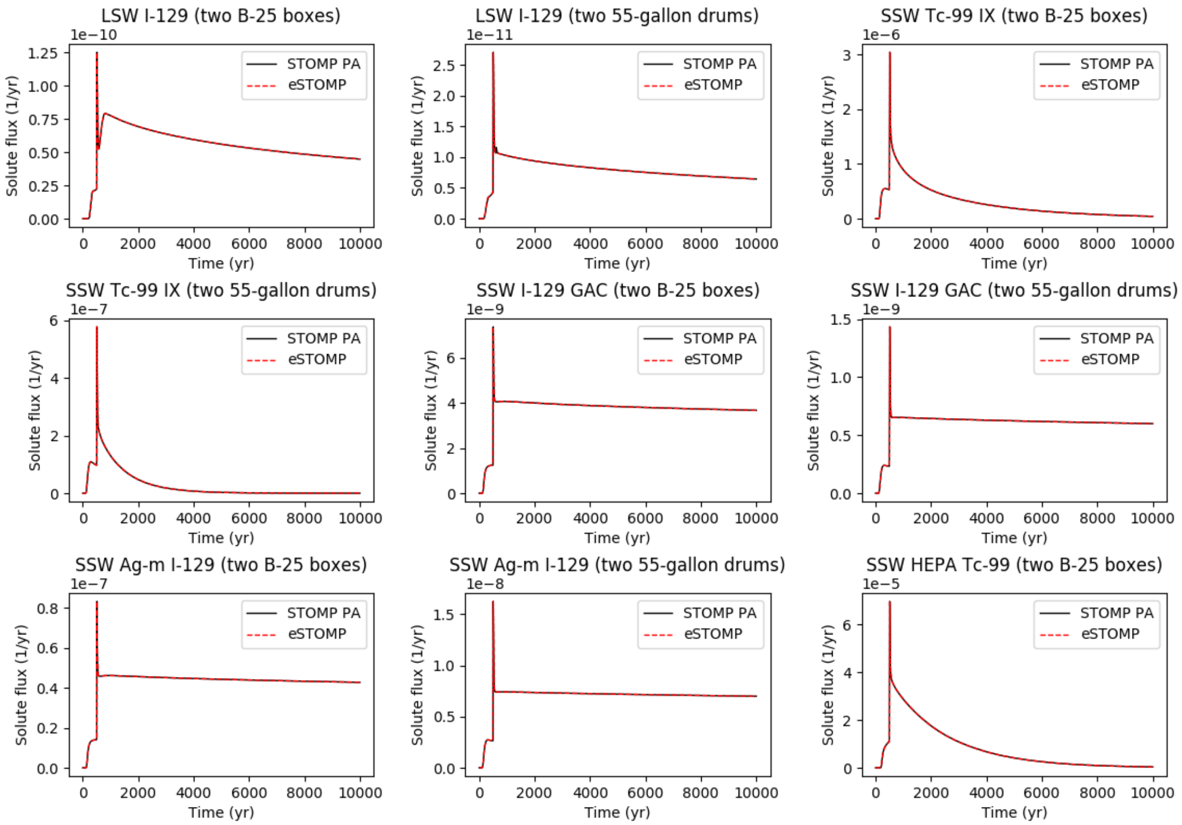

Figure F-7 Comparison of solute fluxes exiting the simulation domain for select LSW and SSW simulations. Benchmark results demonstrate that STOMP and eSTOMP yield the same results.

Figure F-8 shows a comparison eSTOMP and STOMP for SLAW glass simulations comparing the flux of technetium-99 out of the facility and the evolution of pH over time. As with the LSW and SSW simulations, the results are so closely aligned that only one line appears on both charts.

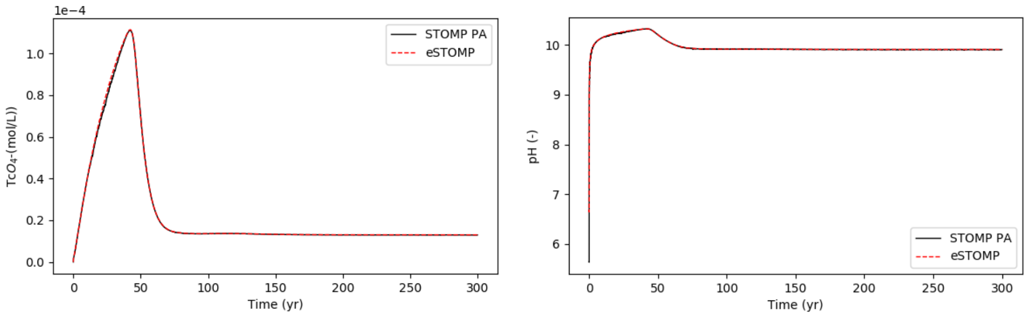

Figure F-8 Comparison of technetium-99 flux exiting the simulation domain (left) and corresponding pH (right). Benchmark results demonstrate that STOMP and eSTOMP yield the same results.

Supplemental Analyses and Simulations

The 2017 IDP PA simulated a range of inventories that might occur, given that the WTP process flowsheet will evolve based on technical knowledge and regulatory decisions. Given that the *exact* inventory is unknown, the approach in this study was to assume an easily scalable inventory within each wasteform simulation. With a unit (or 1 curie) available for release within each simulation, relative release rates can be scaled based on the calculated inventory splits for each of the three scenarios (Cases 1 through 3) simulated in this analysis plus the ILAW glass processing through WTP (Case 0). The estimated inventories are shown in Tables F-13 and F-14 for technetium and iodine, respectively. For example, if SLAW glass is generated (Case 1), nearly 79% of the iodine inventory will be sequestered in the glass. The remaining inventory is captured as both solid secondary waste (SSW) and liquid secondary waste (LSW). (See Table F-13 for Tc-99 splits and Table F-14 for I-129 splits for each wasteform.) Subsequently, solute fluxes exiting the bottom of each domain is converted to a corrosion rate, given as:

$$\text{Corrosion Rate=Flux Rate x Inventory} \tag{F-1}$$

And then translated to a groundwater concentration based on a relationship developed in the 2017 IDF PA, which identified a linear relationship between the peak flux and peak groundwater concentration 100 m downgradient from the disposal facility:

$$Groundwater\ Concentration = \frac{Corrosion\ Rate}{PA\ Corrosion\ Rate}\ x\ (PA\ Peak\ Groundwater\ Concentration) \tag{F-2}$$

Table F-13 Inventory splits for technetium-99 in Ci by wasteform system

Case #	*ILAW Glass*	SLAW Glass	*SLAW Grout*	*Steam Reforming Product*	*SSW (HEPA)*	*LSW*
0	12227				7.93	0.062
1		11793			7.80	0.061
2			11800		.780	
3				11793	7.80	

Table F-14 Inventory splits for iodine-129 in Ci by wasteform system

Case #	*ILAW Glass*	*SLAW Glass*	*SLAW Grout*	*Steam Reforming Product*	*SSW (HEPA)*	*SSW (GAC)*	*LSW*
0	15.0				0.100	3.30	0.030
1		9.48			0.075	2.46	0.022
2			12.01		0.0075	0.0246	
3				11.72	0.075	0.246	

The full stack of wasteform packages is simulated for the maximum depth of the repository. For the B25 gallon containers for the secondary wastes, this means a stack of 8 waste packages are represented in the simulation domain. For the SLAW grout and steam reforming simulations, a maximum stack of 8 waste packages are represented. A stack of four waste packages are represented for the ILAW glass, as shown in Figure F-6.

SLAW Grout

The waste release mechanisms from grout wasteforms are assumed to be driven by diffusion. Unlike glass, where the contaminants are incorporated chemically within the glass matrix and surface matrix dissolution causes the release, contaminants within the grout matrix are believed to be physically encapsulated. Therefore, contaminants will diffuse through the interstitial pore water of the grout matrix to the grout package surface where infiltration water carries the contaminant away from wasteform and the disposal site. Diffusion rates are contaminant specific (Brouns et al. 2003) and so a transport model using molecular diffusion expressions is used. Contaminant-specific diffusion coefficients are calculated from grout leaching test results. In the contaminant diffusion release modeling, the contaminant specific release rates are modeled as a diffusion coefficient and a retardation factor specific to the contaminant of interest. The diffusion coefficient is typically that of species such as sodium, nitrate, and nitrite that are known to generally be representative of the diffusion through the grout without any chemical interactions. The retardation factor and related distribution coefficient (K_d) are then estimated from the ratios of the diffusion coefficients as described by Flach et al. (2016) using equations 25 and 33, reproduced here as Equations F-3 and F-4.

$$R \equiv \left[1 + \frac{(1-n)\rho_s K_d}{Sn}\right] \tag{F-3}$$

$$D_a \equiv \frac{D_e}{R} \tag{F-4}$$

Where

R = Retardation factor,
n = total porosity, volume fraction
ρ_s = solid phase density, g/cm^3
K_d = species-specific distribution coefficient, cm^3/g
Sn = moisture content, volume fraction
D_a = apparent diffusion coefficient, cm^2/s
D_e = effective diffusion coefficient, cm^2/s

For the SLAW grout as well as the LSW and SSW grout wasteforms, three scenarios were executed to estimate the contaminant flux from the IDF. In all cases, given the arid environment at Hanford, and relatively small size of the grout monolith (8.3 m), it was not deemed credible to consider a non-oxidizing condition over long disposal time periods. Therefore, the three scenarios chosen to represent the likely bounding range of grout performance included:

1. Low performing grout based on recommended range of grouted wasteform performance based on laboratory testing
2. High performing grout based on recommended range of grouted SLAW performance based on laboratory testing.
3. Projected best case grout anticipating confirmation of recent enhancements to grout formulations and resulting performance improvements.

Key parameters needed for executing the SLAW Grout simulations are provided in Table F-15. Note that the Grouted LAW wasteform release is described with a diffusion coefficient(or diffusivity) and a calculated distribution coefficient. The distribution coefficients are typically derived from the ranges of effective diffusivities reported by Cantrell et al. (2016). The projected best case technetium distribution coefficient is derived from recent work reported by Asmussen et al. (2016) using a potassium metal sulfide getter to retain the technetium.. The projected best case iodine distribution coefficient is derived from the lower range of results from recent work by Crawford et al. (2017) and Saslow et al. (2017).

Table F-15 Grouted LAW Waste Parameters for SLAW Simulations

	Technetium		Iodine	
	Diffusivity	Distribution Coefficient, K_d	Diffusivity	Distribution Coefficient, K_d
	(cm^2/s)	(m/L)	(cm^2/s)	(m/L)
2017 IDF PA Base Case	NA [a]	NA [a]	NA [a]	NA [a]
Low Performing	6.0E-9 [b]	7.6 [c]	6.0E-9 [b]	0 [f]
High Performing	6.0E-9 [b]	480 [d]	6.0E-9 [b]	0.8 [g]
Projected Best Case	6.0E-9 [b]	4,500 [e]	6.0E-9 [b]	1,000 [h]

[a] 2017 IDF PA did not analyze a grouted SLAW wasteform.
[b] Based on sodium, nitrate, and nitrite diffusivity in SLAW Cast Stone grout. Table 3.1 in Cantrell et al. 2016

[c] Derived from upper range of Tc diffusivity in SLAW Cast Stone grout. Table 3.1 in Cantrell et al. 2016
[d] Derived from lower range of Tc diffusivity in SLAW Cast Stone grout. Table 3.1 in Cantrell et al. 2016
[e] Derived from Tc diffusivity from SLAW Cast Stone with potassium metal sulfide getter. Asmussen et al. 2016
[f] Min value for oxidizing cement. Table 8-4 in Flach et al. 2016
[g] Derived from lower range of I diffusivity in SLAW Cast Stone grout. Table 3.1 in Cantrell et al. 2016
[h] Derived from work with silver zeolite getters by Crawford et al. (2017) and Saslow et al. (2017)

Solid Secondary Waste (SSW)

Processing of the tank wastes will generate secondary wastes, including routine solid wastes. The IDF will receive cement-encapsulated SSW including debris waste, melter consumables, failed process components, silver mordenite beds, ion exchange resins, carbon adsorbent (GAC), and HEPA filters that are to be packaged and macro-encapsulated in grout. The grouted GAC and HEPA filters are specific to LAW and SLAW processing. The diffusivities and distribution coefficients for the grouted GAC and grout macro-encapsulated HEPA filters are shown in Table F-16. As with the SLAW grout wasteform, three cases were considered: low performing, high performing, and projected best case scenarios. The distribution coefficients are typically selected from the ranges of K_ds reported by Flach et al. (2016).

Table F-16 Grout-Encapsulated Granular Activated Carbon and HEPA Filter Solid Secondary Waste Transport Parameters

	Technetium		Iodine	
	Diffusivity	Distribution Coefficient, K_d	Diffusivity	Distribution Coefficient, K_d
	(cm^2/s)	(m/L)	(cm^2/s)	(m/L)
Granular Activated Carbon (GAC)				
PA Base Case	NA [a]	NA [a]	5.4E-8 [g]	302 [h]
Low Performing	3.8E-7 [b]	0 [d]	3.8E-7 [b]	0 [d]
High Performing	6.3E-9 [c]	2 [e]	6.3E-9 [c]	4 [i]
Projected Best Case	6.3E-9 [c]	2,000 [f]	6.3E-9 [c]	10 [e]
HEPA Filters				
PA Base Case	2.9E-8 [j]	0.8 [n]	2.9E-8 [j]	4 [i]
Low Performing	2.0E-6 [k]	0 [d]	2.0E-6 [k]	0 [d]
High Performing	1.0E-9 [l]	2 [e]	1.0E-9 [l]	4 [i]
Projected Best Case	4.2E-10 [m]	2,000 [f]	4.2E-10 [m]	10 [e]

[a] 2017 IDF PA did not analyze Tc release from GAC wasteform.
[b] Sample population maximum for grout with sand (mortar). Table 7-2 in Flach et al. 2016
[c] Sample population lower range for grout with sand (mortar). Table 7-2 and 7-4 in Flach et al. 2016
[d] Min value for oxidizing cement. Table 8-4 in Flach et al. 2016
[e] Max value for oxidizing cement. Table 8-4 in Flach et al. 2016
[f] Max value for reducing cement. Table 8-5 in Flach et al. 2016
[g] Geometric mean for grout with sand (mortar). Table 7-2 and 7-4 in Flach et al. 2016
[h] Average Best I K_d for oxidizing grout and GAC. Table 8-4 and Table 8-7 in Flach et al. 2016
[i] Best value for oxidizing cement. Table 8-4 in Flach et al. 2016
[j] Geometric mean for grout without sand (paste). Table 7-2 and 7-4 in Flach et al. 2016
[k] Sample population maximum for grout without sand (paste). Table 7-2 in Flach et al. 2016
[l] Sample population lower range for grout without sand (paste). Table 7-2 and 7-4 in Flach et al. 2016
[m] Sample population minimum for grout without sand (paste). Table 7-2 in Flach et al. 2016

Liquid Secondary Waste (LSW)

An Effluent Management Facility (EMF) and a companion Effluent Treatment Facility (ETF) are planned to handle off-gas condensates from the LAW vitrification facility. The ETF-treated liquid wastes will then be solidified into a low-temperature, cementitious wasteform that will be disposed of in the IDF. The formulation for the high-sulfate wastes after treatment in the ETF is expected to contain Portland cement, hydrated lime, and blast furnace slag. Similar to the solid secondary waste, waste release mechanisms are assumed to be driven by diffusion. Hence, a transport model using molecular diffusion expressions is used. Diffusion parameters are based on experimental measurements and used in the transport models to predict the flux or rate of release of contaminants from the disposal system to the vadose zone. The diffusivities and distribution coefficients for the grouted LSW are shown in Table F-17. Again, three cases were considered: low performing, high performing, and projected best case scenarios. The distribution coefficients are typically derived from the ranges of diffusivities reported by Cantrell et al. (2016). The projected best case iodine distribution coefficient is derived from recent work reported by Saslow et al. (2017) using a silver zeolite getter to retain the iodine.

Table F-17 Grouted Liquid Secondary Waste Technetium and Iodine Transport Parameters

	Technetium		Iodine	
	Diffusivity	Distribution Coefficient, K_d	Diffusivity	Distribution Coefficient, K_d
	(cm^2/s)	(m/L)	(cm^2/s)	(m/L)
PA Base Case	1.6E-9 [a]	0.8 [b]	1.6E-9 [a]	4 [e]
Low Performing	1.6E-9 [a]	210 [c]	1.6E-9 [a]	0 [f]
High Performing	1.6E-9 [a]	1.6E5 [d]	1.6E-9 [a]	1.7 [g]
Projected Best Case	1.6E-9 [a]	1.6E5 [d]	1.6E-9 [a]	810 [h]

[a] Based on sodium diffusivity in lime-based grout. Table 3.1 in Cantrell et al. 2016

[b] Best value for oxidizing cement. Table 8-4 in Flach et al. 2016

[c] Derived from upper range of Tc diffusivity in lime-based grout. Table 3.1 in Cantrell et al. 2016

[d] Derived from lower range of Tc diffusivity in lime-based grout. Table 3.1 in Cantrell et al. 2016

[e] Best value for oxidizing cement. Table 8-4 in Flach et al. 2016

[f] Min value for oxidizing cement. Table 8-4 in Flach et al. 2016

[g] Derived from lower range of I diffusivity in lime-based grout. Table 3.1 in Cantrell et al. 2016

[h] Derived from hydrated-lime grout with silver zeolite getter. Table 6.7 in Saslow et al. 2017

Steam Reforming Product

Steam reforming generates a granular product that is then encapsulated in a binder material to form a monolithic form that limits contaminant transport and provide structural integrity within the disposal facility. The steam reforming wasteform is a multiphase mineral assemblage of Na-Al-Si (NAS) feldspathoid minerals (sodalite, nosean, and nepheline) with cage and ring structures that sequester anions and cations. A significant uncertainty in earlier assessments (2003 Supplemental Immobilization Risk Assessment and 2012 TC&WM EIS) was data confirming whether Tc and I were incorporated into the mineral structure, and to what extent. Significant research and testing was performed over the past 15 years since the original FBSR assessment. Of particular importance, was that 1) 56-79% of the Tc-99 was found to be captured in the mixed mineral sodalite cage, and the remainder (21-44%) in a reduced, +4 oxidation state as a TcO_2 or $Tc_2S(S_3)_2$, 2) laboratory wasteform testing showed sodalite mineral dissolution was responsible for key contaminant release, and 3) characterization of the mineral phases including published thermodynamic data for many of the mixed mineral phases has been developed. In addition, leach testing of the geopolymer encapsulated granular product was performed in two separate laboratories, producing a range of effective diffusion coefficients.

Similar to glass simulations, a reactive transport simulation approach was initially used to simulate contaminant fluxes out of the disposal facility, assuming a solidified monolith and the ^{99}Tc is in the pertechnetate sodalite

(Schliesser et al. 2017) phases. Similar to the ILAW glass, transition state theory was used to represent the reaction rate law of the steam reforming product as shown in Tables F-18 and F-19. The contaminants (i.e., Tc-99) were assumed to be present in the mineral cage, and only released as minerals underwent dissolution. This assumed that the process conditions enabled high incorporation of the contaminants into the cage structure. This approach did not account for the evidence of reduced technetium outside the sodalite cage but retained in the mixed mineral phase. Furthermore, test data was not available to provide confidence in the rate law parameters. Therefore, this approach was used as a sensitivity case only.

Table F-18 Rate law parameters for minerals in steam reformed product.

Mineral Phase	$\vec{k}_0$	K_g[a]	η	E_a
	Converted[b] Forward Rate Constant (mol/[m^2 s])	Equilibrium Constant Based on Activity Product	pH Power Law Coefficient	Activation Energy (kJ/mol)
Nosean	2.5E-01	-92.1	0	48.6
Nepheline	1.0E-09	-9.39	-0.251	16.6
Pertechnetate sodalite	2.5E-01	-92.1	0	48.6

Table F-19 Aqueous species and stoichiometry for minerals in steam reformed product.

Mineral	Aqueous Species	Stoichiometric Coefficient
Nosean	AlO^{2-}	6.0
	Na	8.0
	SiO_2(aq)	6.0
	SO_4^{2-}	1.0
	TcO_4-	0.1
Nepheline	AlO_2^-	0.9874
	Ca^{2+}	0.0206
	K^+	0.0225
	Li^+	0.1250
	Na^+	0.7225
	SiO_2(aq)	0.7700
	$Ti(OH)_4$(aq)	0.370
Cl-sodalite	AlO^{2-}	6.06
	Na	8.04
	SiO_2(aq)	5.94
	Cl^-	1.92
Pertechnetate-sodalite	AlO^{2-}	6.0
	Na	8.0
	SiO_2(aq)	6.0
	TcO_4-	TBD

Because there was low confidence in the data supporting a reactive transport approach, a diffusive release approach was used to represent contaminant releases from the geopolymer matrix. Similar to the grout wasteforms, the contaminant specific release rates were modeled with a diffusion coefficient and distribution coefficient specific to the contaminant of interest. The diffusion coefficient is assumed to be equivalent to sodium diffusion, representing diffusion within grouts without any chemical interactions. The retardation factor and related distribution coefficient (K_d) are then estimated from the ratios of the diffusion coefficients for rhenium (as a surrogate for technetium) and iodine as described by Flach et al. (2016) using equations F-1 and F-2 above.

Jantzen et al. (2013) provide information on FBSR product encapsulated in fly ash and clay based geopolymer materials. Appendix G of that report includes the results of diffusion leach tests for several species including rhenium, iodine, and sodium. For this study, the reported diffusion coefficients for leach times from 19 through 107 days were averaged for the five different FBSR/geopolymer combinations. Single diffusivities for each species were then based on the geometric average of the five combinations. Jantzen et al. (2013) provide densities but not porosities or moisture contents to convert retardation factors to distribution coefficients (K_ds). Therefore, grout properties were used when geopolymer properties were not available. Table F-20 provides the diffusivities and distribution coefficients used in this analysis.

Table F-20 FBSR Product Encapsulated in Geopolymer SLAW Technetium and Iodine Transport Parameters

	Technetium		Iodine	
	Diffusivity	Distribution Coefficient, K_d	Diffusivity	Distribution Coefficient, K_d
	(cm^2/s)	(m/L)	(cm^2/s)	(m/L)
PA Base Case	NA [a]	NA [a]	NA [a]	NA [a]
Low Performing	1.3E-10 [b]	2 [c]	1.3E-10 [b]	8 [d]
High Performing	1.3E-10 [b]	55 [c]	1.3E-10 [b]	550 [d]
Projected Best Case	1.3E-10 [b]	175 [c]	1.3E-10 [b]	3,000 [d]

[a] 2017 IDF PA did not analyze a FBSR SLAW wasteform.

[b] Based on sodium diffusivity in FBSR product encapsulated in fly ash and clay geopolymers. Tables G-3, G-4, G-5, G-8, G-9, and G-12 in Jantzen et al. 2013

[c] Derived from range of rhenium diffusivities reported in Tables G-3, G-4, G-5, G-8, G-9, and G-12 in Jantzen et al. 2013

[d] Derived from range of iodine diffusivities reported in Tables G-3, G-4, G-5, G-8, G-9, and G-12 in Jantzen et al. 2013

Simulation Results

Fractional release rates presented are based on a one curie inventory so that the relative rates, independent of inventory, can be evaluated. Results of simulations are presented in the following order: 1) secondary waste predictions for LSW, SSW-HEPA, and SSW-GAC, 2) SLAW Grout, 3) Steam Reforming, and 4) Glass.

LSW Flux Predictions

Plotted in Figure F-9 are the fractional solute flux rates (for both Tc-99 and I-129) for LSW. Note that for both solutes, the peak fluxes occur after 500 years, driven by the initial moisture content in the IDF once the wasteforms are in place. Like the 2017 IDF PA, no recharge enters the facility during the first 100 years, followed by a 0.5 mm/yr recharge rate for the next 400 years. The surface barrier is expected to degrade over time. To model this, at 500 years, at step change is made such that the recharge rate is increased to 3.5 mm/yr for the remainder of the 10,000-year simulation.

The Projected Best Case for both Tc-99 and I-129 predicts a fractional release rate that is 3-5 orders of magnitude lower than the low-performing parameter set. The PA Base Case for I-129 was pessimistic as it predicted fluxes that were nearly one order of magnitude higher than the low performing case.

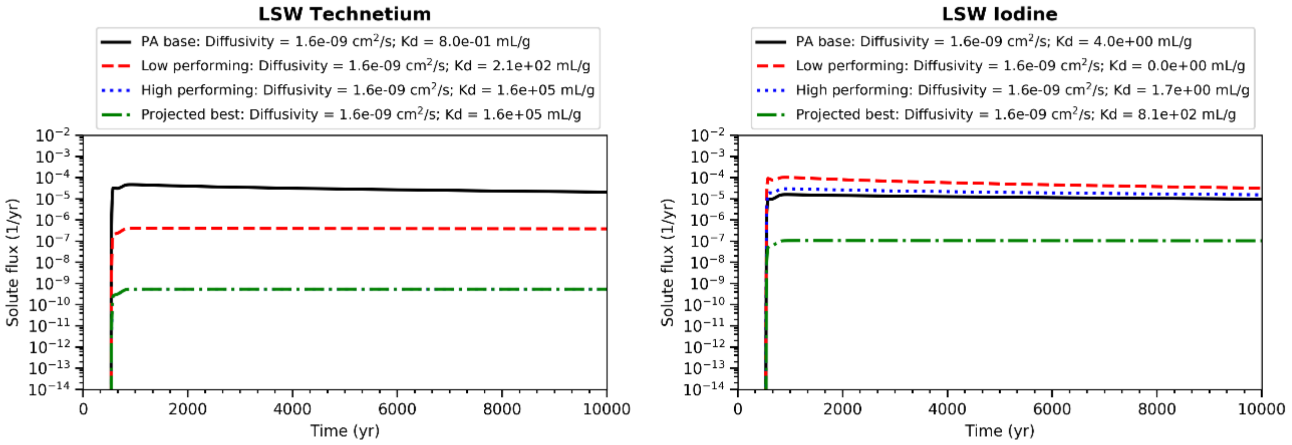

Figure F-9. Fractional solute flux for technetium-99 (left) and iodine-129 (right) for LSW.

SSW Flux Predictions

The fractional release rates for SSW are shown in Figure F-10, for both HEPA filters (Tc-99 and I-129) and GAC (I-129 only). Large differences exist between the high performing and low performing cases due to differences in the assumed distribution coefficient. For example, the Tc-99 fractional release rate for the high performing wasteform is so small that it plots along the baseline of the graph (10^{-14} 1/yr) and is not visible. For low performing solid wasteforms, the distribution coefficient is assumed to be zero, causing the peak release rate for the GAC to occur after 1000 years. For all other cases, the distribution coefficient is high enough (2 – 2000 mL/g) to reduce the fractional release rates by several orders of magnitude relative to the low performing, zero distribution coefficient case.

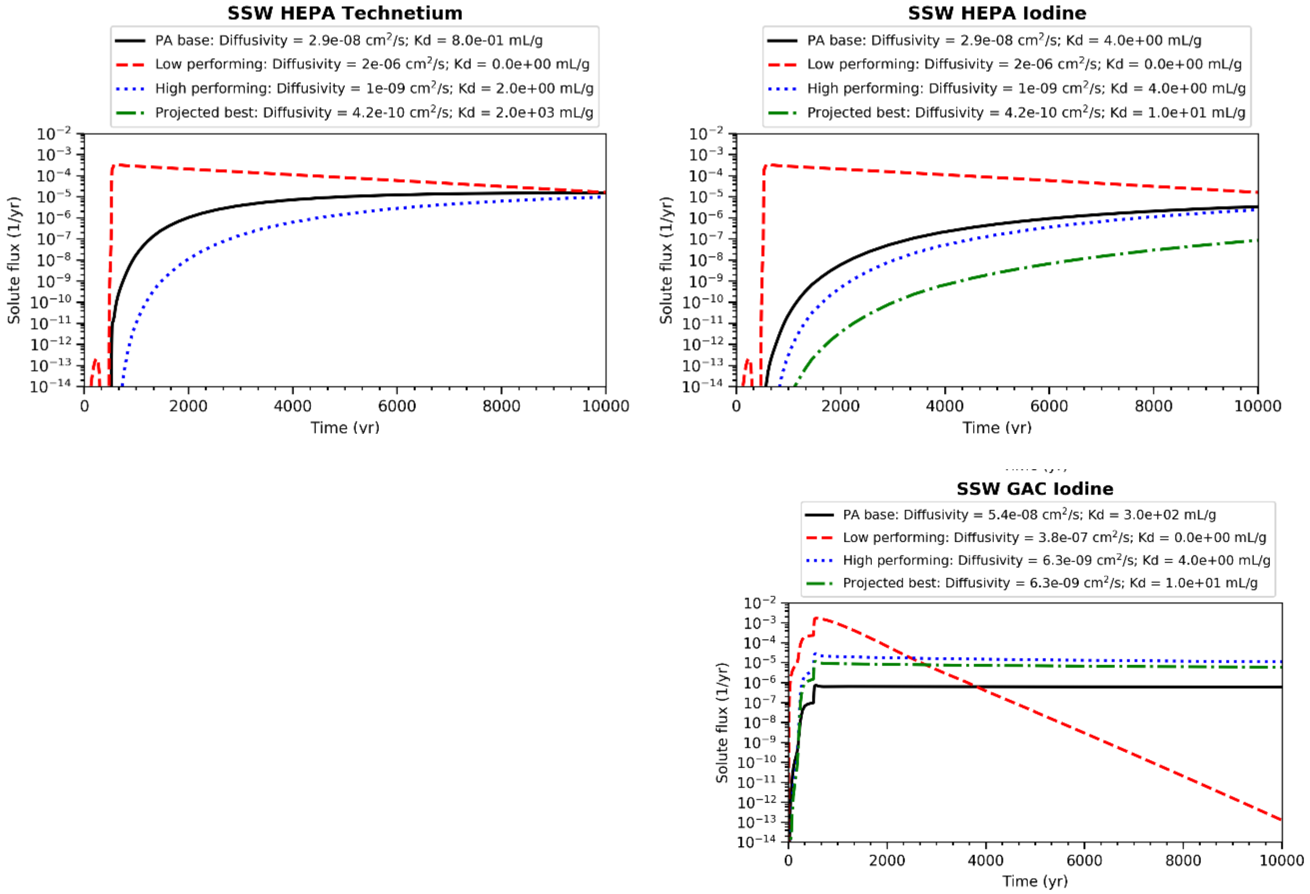

Figure F-10. Fractional solute flux for technetium-99 (left) and iodine-129 (right) for SSW .

SLAW Grout Flux Predictions

The grouted SLAW wasteform fractional release rates are shown in Figure F-11 for both Tc-99 and I-129. High distribution coefficients used to represent contaminant retention are effective under the low recharge regime that occurs before the step change in recharge rate equated with the surface barrier degradation. Once the fractional release rates reach a steady state, they only vary over a few orders of magnitude among the four different parameter sets.

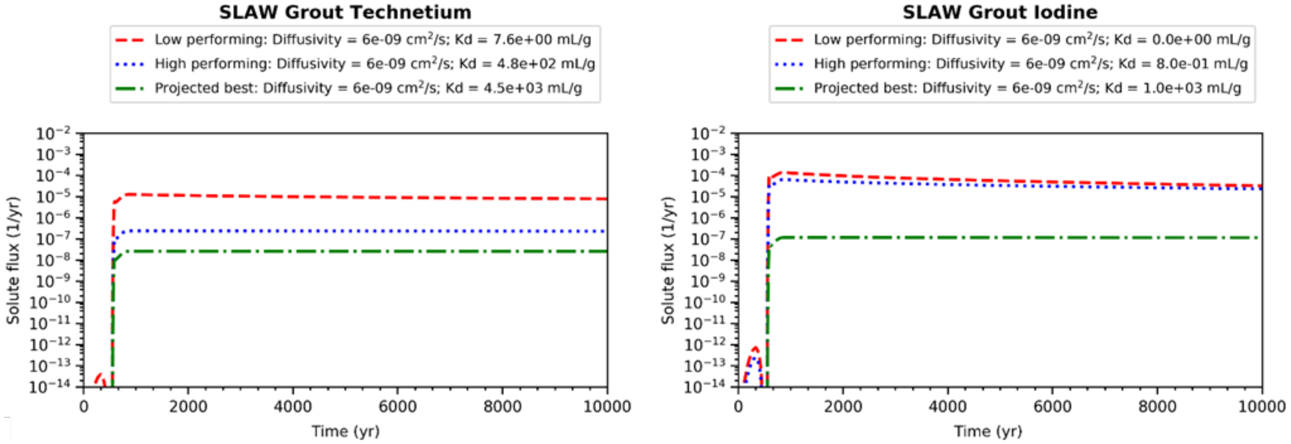

Figure F-11. Fractional solute flux for technetium-99 (left) and iodine-129 (right) for SLAW Grout.

Steam Reforming Flux Predictions

The fluidized bed steam reforming (FBSR) wasteform fractional release rates are shown in Figure F-12 for both Tc-99 and I-129 and are distinguished only by their differences in distribution coefficient. Iodine is retained more strongly within the steam reforming product relative to Tc-99, but the fractional flux rate ranges are similar between the two contaminants. The parameters associated with a high performing wasteform yield a fractional flux rate lower than the SLAW grout. A sensitivity case using a reactive transport simulation with rate parameters is shown in Figure F-12. Absent new rate parameters for the sodalite mineral, the nosean mineral rate parameters from the prior 2003 Supplemental Treatment Risk Assessment were applied. The resulting simulation produced a peak solute flux of 5E-07 per year, within the range of fractional release rates derived from the diffusive release data.

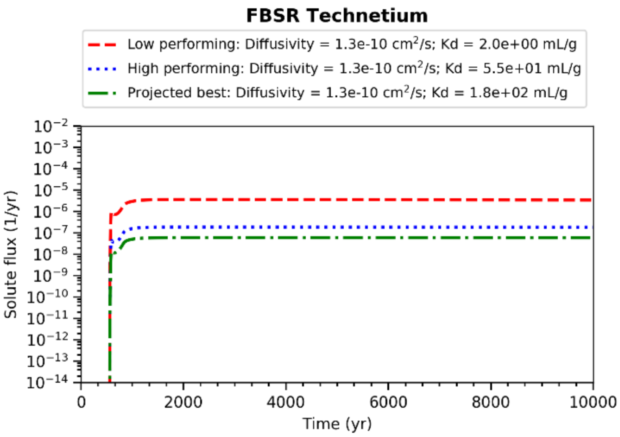

Figure F-12 Fractional solute flux for technetium-99 (left) and iodine-129 (right) for steam reforming product

Glass Predictions

The LAWA44 glass represented the glass release in the 2017 IDF PA. An advanced glass was also simulated because waste loading is higher than the base glass formulations, although the release rate is not necessarily lower. The fractional release rate shown in Figure F-13 represents the release rate for both Tc-99 and I-129 and is similar for both glass formulations. The fractional release rate is the same order of magnitude as the Projected Best Case for I-129 for LSW and SLAW Grout.

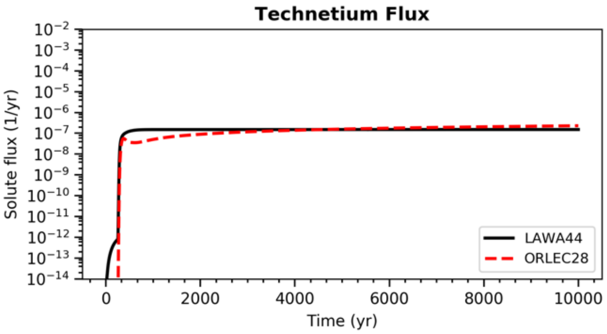

Figure F-13. Fractional solute flux for technetium-99 for glass (iodine-129 assumed to have same rate)

Projected Groundwater Impacts

Transport from the bottom of the IDF through the vadose zone to groundwater was modeled in the 2017 IDF PA, and a linear relationship between peak unit release rate and peak groundwater concentration at the point of compliance was reported[102]. This study used the PA-based relationship rather than simulating the vadose zone and groundwater transport as shown in Equations F-1 and F-2 since a perfect linear relationship was identified ($R^2 = 1$). This approach is consistent with the method used in the 2003 Supplemental LAW Risk Assessment (Mann et al, 2003). Tables F-21 through F-23 summarize the fractional release rates based on a unit release, total inventories disposed for each wasteform over the ranges of parameter sets evaluated. Projected peak groundwater concentrations at the point of compliance are also shown in the final column of each table but are more easily visualized in Figure F-14. Although time of peak groundwater concentration was not assessed in this study, time of peak flux is identified in each table. Based on the 2017 IDF PA results, peak groundwater concentrations will occur after the 1000-year time of compliance.

Figure F-14 shows the predicted groundwater concentrations for technetium-99 for a point-of-compliance well located 100 m downgradient from the IDF. Each bar graph represents the three systems of wasteforms evaluated. SLAW glass, for example, consists of glass, LSW and SSW; SLAW grout consists of grout and SSW; and Steam Reforming consists of steam reforming product and SSW. Stacked bars represent the relative contribution to the peak concentration for the Low Performing, High Performing and Projected Best parameter sets. Note that only a low-performing SLAW grout yields Tc-99 concentrations above the 900 pCi/L drinking water standard (DWS). Although a low-performing steam reforming product predicts the Tc-99 below the DWS, the concentration is on the same order of magnitude (~500 pCi/L). However, the high performing and projected best cases are protective and do not exceed the DWS.

Figure F-15 shows the predicted groundwater concentrations for iodine-129 for a well located 100 m downgradient from the IDF. Similar to Figure F-14, each bar graph represents the three systems of wasteforms evaluated, with the stacked bars representing the relative contribution to the peak concentration for the Low Performing, High Performing and Projected Best parameter sets. The drinking water standard (DWSO) for I-129 is 1 pCi/L, and would plot along the baseline of all the I-129 charts. For both the glass and steam reforming systems, Tables F-21 and F-22 show that the low-performing SSW GAC is responsible for the I-129 DWS exceedance. For the SLAW grout system, both the low- and high-performing cause the I-129 DWS to be exceeded. Compliance with the I-129 DWS is more difficult than with Tc-99 because it is so small and is the lowest DWS of all radionuclides on the federal register.

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[102] Personal communication with K. Pat Lee, Orano Federal Services, March 19, 2019

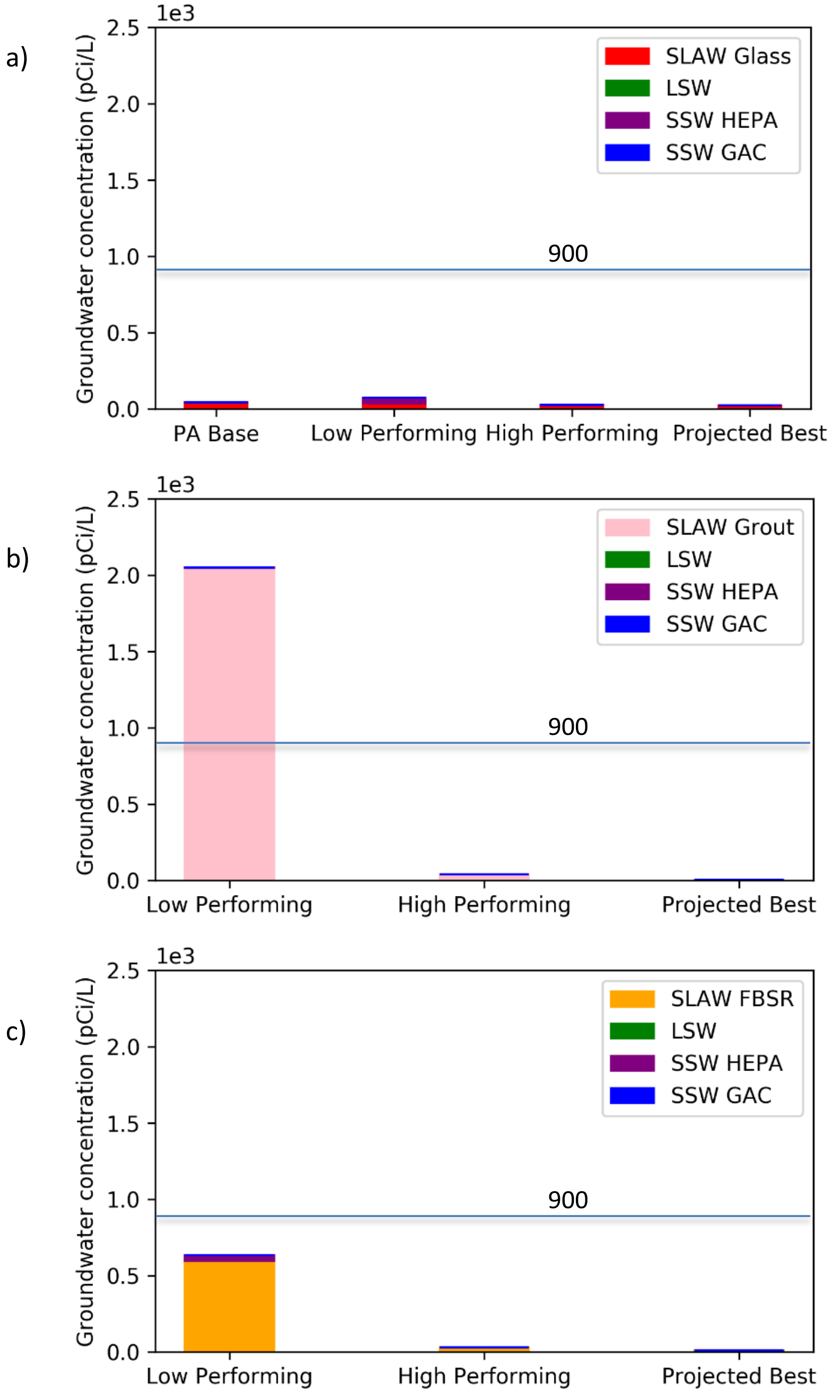

Figure F-14. Predicted technetium-99 groundwater concentrations for 100 m downgradient compliance well for a) SLAW Glass, b) SLAW Grout, and c) SLAW Steam Reforming (FBSR) systems. Stacked columns represent the relative contribution to the peak concentration for the Low Performing, High Performing and Projected Best parameter sets. Note that only a low-performing Steam Reforming product yields a Tc-99 concentration above the 900 pCi/L drinking water standard.

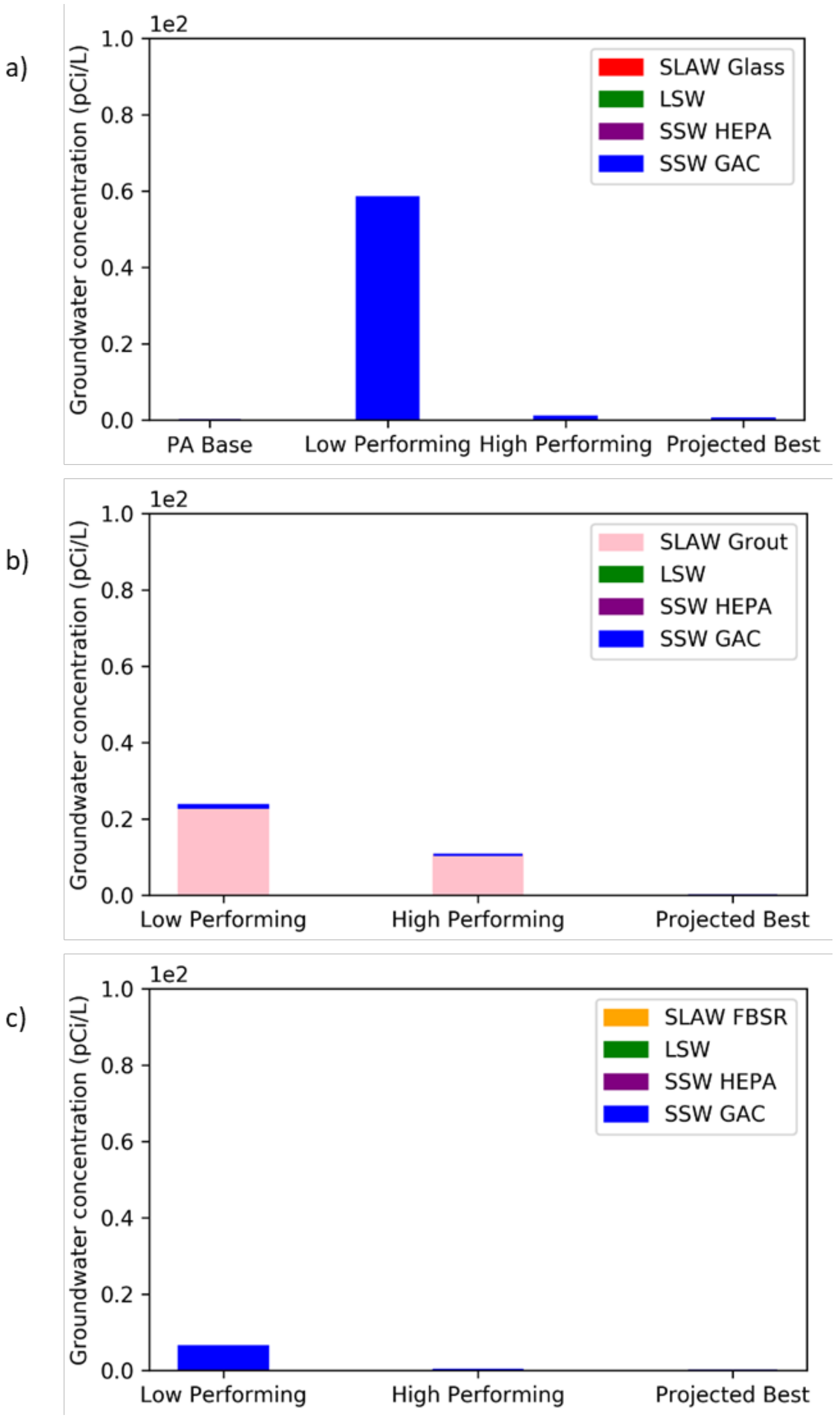

Figure F-15. Predicted iodine-1 29 groundwater concentrations for 100 m downgradient compliance well for a) SLAW Glass, b) SLAW Grout, and c) SLAW Steam Reforming (FBSR) systems. Stacked columns represent the relative contribution to the peak concentration for the Low Performing, High Performing and Projected Best parameter sets.

Table F-21 Projected Peak Groundwater Impacts for SLAW Glass Cases Evaluated

Waste[2]	PE Simulation Case	Flux out of Bottom of IDF[1]				Disposed Inventory		Peak Groundwater Concentration at Point of Compliance[3]	
		Technetium		Iodine					
		Peak value (1/yr)	Peak time (yr)	Peak value (1/yr)	Peak time (yr)	Tc-99 (Ci)	I-129 (Ci)	Tc-99 (pCi/L)	I-129 (pCi/L)
LSW	PA Base Case	4.66E-05	9.15E+02	1.58E-05	9.49E+02	0.061	0.022	3.94E-02	4.87E-03
	Low Performing	4.05E-07	1.04E+03	1.03E-04	9.15E+02	0.061	0.022	3.43E-04	3.17E-02
	High Performing	5.39E-10	1.63E+03	2.97E-05	9.15E+02	0.061	0.022	4.56E-07	9.15E-03
	Projected Best Case	5.39E-10	1.63E+03	1.06E-07	1.16E+03	0.061	0.022	4.56E-07	3.26E-05
SSW HEPA	PA Base Case	1.55E-05	1.00E+04	3.42E-06	1.00E+04	7.80	0.075	1.67E+00	3.55E-03
	Low Performing	3.54E-04	5.94E+02	3.54E-04	5.94E+02	7.80	0.075	3.80E+01	3.68E-01
	High Performing	9.81E-06	1.00E+04	2.43E-06	1.00E+04	7.80	0.075	1.05E+00	2.53E-03
	Projected Best Case	0	-	8.63E-08	1.00E+04	7.80	0.075	0.00E+00	8.97E-05
SSW GAC	PA Base Case	-	-	7.31E-07	5.60E+02	0	2.46	0.00E+00	2.51E-02
	Low Performing	3.68E-06	2.20E+03	1.69E-03	5.60E+02	0	2.46	0.00E+00	5.79E+01
	High Performing	1.88E-07	2.00E+03	2.86E-05	5.60E+02	0	2.46	0.00E+00	9.79E-01
	Projected Best	5.99E-08	2.20E+03	1.19E-05	5.60E+02	0	2.46	0.00E+00	4.08E-01
SLAW	PA Base Case	2.57E-07	2.00E+03	2.57E-07	2.00E+03	11793	9.48	4.18E+01	3.39E-02
	Low Performing	2.29E-07	1.00E+04	2.29E-07	1.00E+04	11793	9.48	3.72E+01	3.02E-02
	High Performing	2.29E-07	1.00E+04	2.29E-07	1.00E+04	11793	9.48	3.72E+01	3.02E-02
	Projected Best Case	1.51E-07	1.00E+04	1.51E-07	1.00E+04	11793	9.48	2.46E+01	2.00E-02

1 - Assumes 1 Ci each of Tc-99 and I-129 present in waste resulting in a unit release rate or "flux" in units of Ci released/Ci disposed/yr (1/yr). Reported flux is independent of inventory that is projected to be disposed in each waste form.

2 - LSW not included as SLAW FBSR case does not produce LSW

3 - Red text-highlight indicates predicted peak groundwater concentration exeeds EPA groundwater maximum contaminant level for Tc-99 (900 pCi/L) or I-129 (1 pCi/L)

Table F-22 Projected Peak Groundwater Impacts for SLAW Fluidized Bed Steam Reforming Cases Evaluated

		Flux out of Bottom of IDF[1]						Peak Groundwater Concentration at Point of Compliance[3]	
		Technetium		Iodine		Disposed Inventory			
Waste[2]	**PE Simulation Case**	**Peak value (1/yr)**	**Peak time (yr)**	**Peak value (1/yr)**	**Peak time (yr)**	**Tc-99 (Ci)**	**I-129 (Ci)**	**Tc-99 (pCi/L)**	**I-129 (pCi/L)**
LSW	PA Base Case	4.66E-05	9.15E+02	1.58E-05	9.49E+02	0	0	0.00E+00	0.00E+00
	Low Performing	4.05E-07	1.04E+03	1.03E-04	9.15E+02	0	0	0.00E+00	0.00E+00
	High Performing	5.39E-10	1.63E+03	2.97E-05	9.15E+02	0	0	0.00E+00	0.00E+00
	Projected Best Case	5.39E-10	1.63E+03	1.06E-07	1.16E+03	0	0	0.00E+00	0.00E+00
SSW HEPA	PA Base Case	1.55E-05	1.00E+04	3.42E-06	1.00E+04	7.80	0.075	1.67E+00	3.55E-03
	Low Performing	3.54E-04	5.94E+02	3.54E-04	5.94E+02	7.80	0.075	3.80E+01	3.68E-01
	High Performing	9.81E-06	1.00E+04	2.43E-06	1.00E+04	7.80	0.075	1.05E+00	2.53E-03
	Projected Best Case	0	-	8.63E-08	1.00E+04	7.80	0.075	0.00E+00	8.97E-05
SSW GAC	Low Performing	1.69E-03	5.60E+02	1.69E-03	5.60E+02	0	0.246	0.00E+00	5.79E+00
	High Performing	5.41E-05	5.46E+02	2.86E-05	5.60E+02	0	0.246	0.00E+00	9.79E-02
	Projected Best Case	6.19E-08	5.60E+02	1.19E-05	5.60E+02	0	0.246	0.00E+00	4.08E-02
SLAW	PA Base Case	-	-	-	-	11793	11.7		
	Low Performing	3.68E-06	2.20E+03	1.16E-06	2.00E+03	11793	11.7	5.97E+02	1.89E-01
	High Performing	1.88E-07	2.00E+03	1.92E-08	2.44E+03	11793	11.7	3.05E+01	3.13E-03
	Projected Best Case	5.99E-08	2.20E+03	3.52E-09	2.75E+03	11793	11.7	9.74E+00	5.74E-04

1 - Assumes 1 Ci each of Tc-99 and I-129 present in waste resulting in a unit release rate or "flux" in units of Ci released/Ci disposed/yr (1/yr). Reported flux is independent of inventory that is projected to be disposed in each waste form.

2 - LSW not included as SLAW FBSR case does not produce LSW

3 - Red text-highlight indicates predicted peak groundwater concentration exeeds EPA groundwater maximum contaminant level for Tc-99 (900 pCi/L) or I-129 (1 pCi/L)

Table F-23 Projected Peak Groundwater Impacts for SLAW Grout Cases Evaluated

		Flux out of Bottom of IDF[1]				Disposed Inventory		Peak Groundwater Concentration at Point of Compliance[3]	
		Technetium		Iodine					
Waste[2]	**PE Simulation Case**	**Peak value (1/yr)**	**Peak time (yr)**	**Peak value (1/yr)**	**Peak time (yr)**	**Tc-99 (Ci)**	**I-129 (Ci)**	**Tc-99 (pCi/L)**	**I-129 (pCi/L)**
LSW	PA Base Case	4.66E-05	9.15E+02	1.58E-05	9.49E+02	0	0	0.00E+00	0.00E+00
	Low Performing	4.05E-07	1.04E+03	1.03E-04	9.15E+02	0	0	0.00E+00	0.00E+00
	High Performing	5.39E-10	1.63E+03	2.97E-05	9.15E+02	0	0	0.00E+00	0.00E+00
	Projected Best Case	5.39E-10	1.63E+03	1.06E-07	1.16E+03	0	0	0.00E+00	0.00E+00
SSW HEPA	PA Base Case	1.55E-05	1.00E+04	3.42E-06	1.00E+04	0.780	0.00747	1.67E-01	3.55E-04
	Low Performing	3.54E-04	5.94E+02	3.54E-04	5.94E+02	0.780	0.00747	3.80E+00	3.68E-02
	High Performing	9.81E-06	1.00E+04	2.43E-06	1.00E+04	0.780	0.00747	1.05E-01	2.53E-04
	Projected Best Case	NA	NA	8.63E-08	1.00E+04	0.780	0.00747	0.00E+00	8.97E-06
SSW GAC	Low Performing	1.69E-03	5.60E+02	1.69E-03	5.60E+02	0	0.0246	0.00E+00	5.79E-01
	High Performing	5.41E-05	5.46E+02	2.86E-05	5.60E+02	0	0.0246	0.00E+00	9.79E-03
	Projected Best Case	6.19E-08	5.60E+02	1.19E-05	5.60E+02	0	0.0246	0.00E+00	4.08E-03
SLAW	Low Performing	1.26E-05	8.99E+02	1.38E-04	8.49E+02	11800	12.0	2.05E+03	23.06
	High Performing	2.44E-07	1.07E+03	6.33E-05	8.58E+02	11800	12.0	3.97E+01	10.58
	Projected Best Case	2.62E-08	1.27E+03	1.18E-07	8.58E+02	11800	12.0	4.26E+00	0.02

NA - Simulation case did not result in flux out of IDF within 10,000 year simulation time period.

1 - Assumes 1 Ci each of Tc-99 and I-129 present in waste resulting in a unit release rate or "flux" in units of Ci released/Ci disposed/yr (1/yr). Reported flux is independent of inventory that is projected to be disposed in each waste form.

2 - LSW not included as SLAW Grout case does not produce LSW

3 - Red text-highlight indicates predicted peak groundwater concentration exeeds EPA groundwater maximum contaminant level for Tc-99 (900 pCi/L) or I-129 (1 pCi/L)

Summary and Conclusions

The analysis presented in this appendix demonstrates the importance of considering contaminant fractional release rates relative to their total inventories. Once a fractional release rate was converted to a corrosion rate based on total inventory, a peak groundwater concentration was calculated and relative contributions to the peak concentration could be identified. To account for a range in waste performance, parameter sets were identified that represented low performing, high performing and a projected best case. For the latter, it is assumed that wasteform performance will eventually meet that standard.

For the low-performing parameter sets, only the SLAW grout exceeded the Tc-99 DWS. For I-129, however, the low-performing GAC SSW caused the DWS exceedance for both the SLAW glass and steam reforming systems. The I-129 DWS was also exceeded for low-performing grout.

If only the best projected cases are considered, then no exceedance of the Tc-99 and I-129 DWS occurs. Figure F-16a) shows that SLAW glass system will release the highest Tc-99 concentrations, but the peak concentration of ~25 pCi/L is well below the 900 pCi/L DWS. The glass system also shows the highest concentrations of I-129 of all three systems, with a peak concentration of ~0.6 pCi/L, which is just below the 1 pCi/L standard. A smaller risk of exceeding the 1 pCi/L DWS for I-129 exists for the SLAW grout and steam reforming systems because the peak groundwater concentration is at least an order of magnitude smaller than the standard.

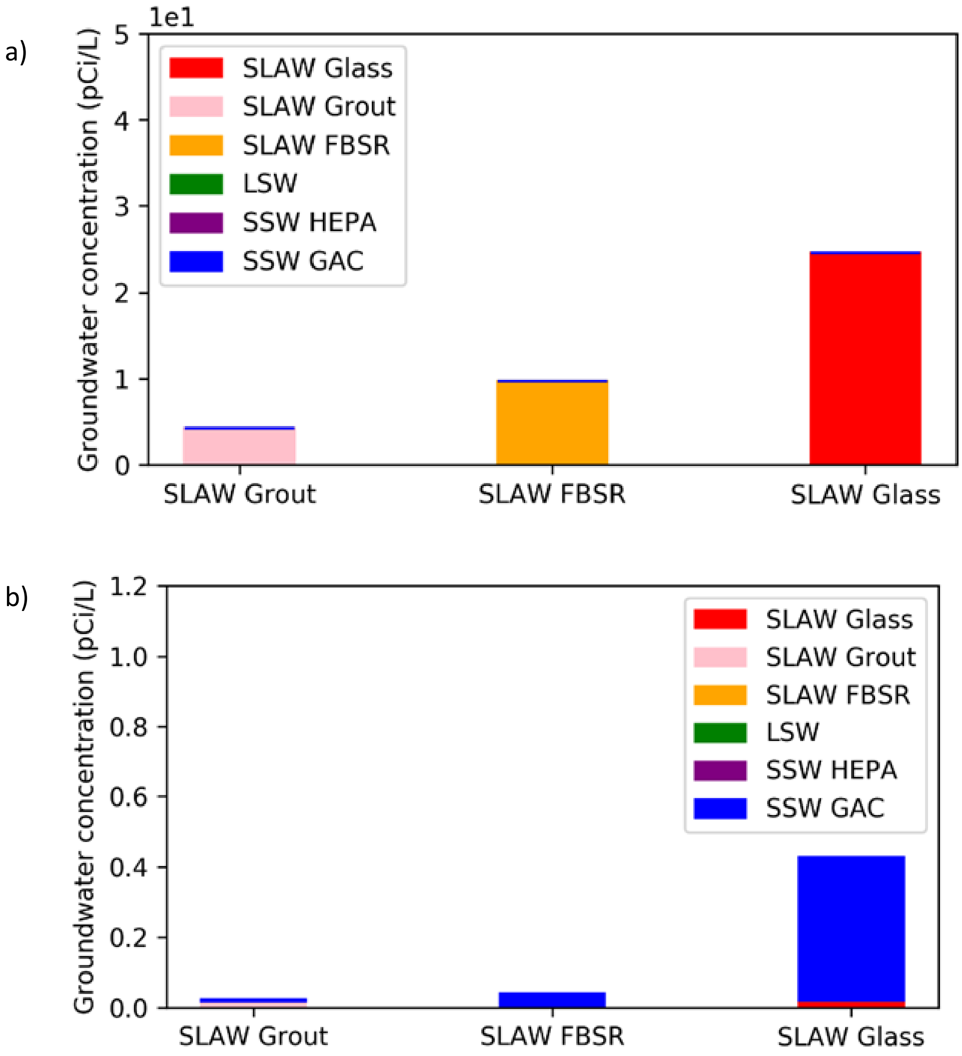

Figure F-16. Best Projected Cases for a) Tc-99 and b) I-129 for all three wasteform systems

F.5 WASTE CONTROL SPECIALISTS

F.5.1 General Description

Waste Control Specialists, LLC is a treatment, storage and disposal company dealing in radioactive, hazardous, and mixed wastes. Their primary facilities are located on 1,338 acres (540 hectares) of land that is 35 miles (56 km) west of Andrews, Texas and 5 miles (8 km) east of Eunice, New Mexico.

Waste Control Specialists' treatment capabilities include dewatering, stabilization and repackaging. Their transportation capabilities include ownership of three Type B shipping casks and two Type A shipping containers. They have three separate disposal facilities for radioactive wastes, including (1) a facility for disposal of "commercial" radioactive wastes from the Texas Low Level Radioactive Waste Disposal Compact, and radioactive wastes imported from 36 other states into the Texas Compact, (2) a facility for disposal of 11e(2) byproduct material[103], and (3) the Federal Waste Disposal Facility (FWF). Figure F-17 is an aerial photograph of

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[103] The Atomic Energy Act, as revised in 1978 and in 2005, defines byproduct material in Section 11e.(2) as the tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content (simplistically, 11e.(2) byproduct material is uranium or thorium mill tailings).

the disposal facilities for radioactive wastes at WCS. The remainder of this subsection focuses exclusively on the FWF, which was designed, licensed, and constructed for “federal waste” disposal, including all wastes from the DOE.

F.5.1.1 Physical Setting

The area surrounding the WCS’s facilities is sparsely-populated, and (on average) receives less than 16 inches (400 mm) of rainfall per year. Based on an extensive site investigation program, including over 500 wells and core samples, the geology and hydrology of the WCS site is well understood and relatively interesting.

The WCS facilities are located over a geologic feature referred to as the “buried red ridge.[104]” This buried red ridge is composed of Triassic-age sediments of the Dockum Group. The Dockum Group consists of a series of fluvial and lacustrine mudstones, siltstones, sandstones, and silty dolomite deposits that are over 1,000 feet thick beneath the WCS site. The buried red ridge (i.e., the Dockum Group) is encountered at depths ranging from about 8 to 80 feet beneath the WCS facilities.

In the subsurface, the Ogallala, Antlers and Gatuňa geologic formations occur to the north and east of the buried red ridge. These three formations were deposited in different geologic time periods but occupying nearly the same stratigraphic position. The Antlers Formation is the oldest and was deposited in earliest Cretaceous time, whereas the Ogallala Formation is Tertiary in age with deposition occurring between 2 and 6 million years ago. The Antlers formation forms a veneer over the crest of the buried red ridge, with the Ogallala lying to the northeast and Gatuňa lying to the southwest of the ridge.

The Ogallala Formation, if present above the buried red ridge, is not water bearing in the WCS area. However, the Ogallala is saturated to the north and east of the buried red ridge and regionally, the Ogallala Formation is the primary freshwater aquifer and it serves as the principal source of groundwater in the Southern High Plains.

In the Dockum Group beneath the WCS facilities, there are transmissive zones in discontinuous sandstones/siltstones. The uppermost laterally continuous, and continuously saturated, transmissive zone is a 10- to 35-foot thick sandstone/siltstone at a depth of about 225 feet. This unit, referred to as the 225-foot zone, has a very low permeability of approximately 10^{-8} cm/s. WCS has monitor wells screened in the 225-foot zone in all three landfill areas. Because of the low transmissivity and salinity, the 225-foot zone is not classified as a drinking water aquifer. In fact, the WCS facilities are not located over a drinking water aquifer or adjacent to any underground drinking water supply.[105] This lack of a groundwater pathway has a positive influence on the WAC as discussed in Section F.5.4.1.

F.5.1.2 Disposal Facility Design

Wastes are emplaced 25 to 120 feet (~8 to 37 m) below the land surface in the FWF disposal cell that includes a 7-foot (2-m) thick multi-barrier liner. When constructed, the multi-barrier cap over the cell will be a minimum of 25 feet (~8 m) thick and will be completed at-grade. Higher-activity Class B and C LLW and MLLW are disposed in Modular Concrete Canisters (MCCs) inside the disposal cell. The MCCs are 6-inch (150-mm) thick, steel reinforced concrete containers. The natural barriers (e.g., no drinking water aquifer and thick red clay beds) and the engineered barriers (e.g., 2-m -thick multi-barrier liner and MCCs) work together to give WCS one of the most robust multi-barrier design of any Agreement State-licensed LLW disposal facility in the United States.

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[104] Much of the description of the hydrogeology is extracted from: Chapter 2 of the *WCS Consolidated Interim Storage Facility System Safety Analysis Report (Public Version)* Docket Number 72-1050 Revision 2 (7/19/2018) https://www.nrc.gov/docs/ML1822/ML18221A408.html

[105] Much of this information is from the WCS website at http://www.wcstexas.com/about-wcs/environment/

Waste Control Specialists uses two standard types of MCC: (1) cylindrical: 6-foot (’) and (2) rectangular: 9’ 6” L x 7’ 8” W x 9’ 2” H (internal). Typically, Class B and C LLWs, inside their DOT shipping container, are placed in an MCC and any void space is grouted, and the concrete lid is placed on top. A waste that is disposed in a MCC is categorized by WCS as a *containerized waste*. In contrast, *bulk wastes* may be shipped in reusable Department of Transportation (DOT) shipping containers, the wastes are not disposed in the DOT shipping container, and the waste is not placed in a MCC. Bulk waste is acceptable for disposal in the FWF, if it is Class A and has a dose rate of <100 mrem at 30 centimeter (cm) (~1 ft). Bulk waste is sometimes disposed in an MCC, for example, if the dose rate of the bulk waste is >100 mrem at 30 cm (~1 ft). Figure F-18 shows wastes being placed in a rectangular MCC.

To facilitate waste handling, this study assumes the primary WFs will be shipped and disposed using 8.4 m3 “soft side” shipping containers. With a capacity of 8.4 m3 each (11 yards3), two soft-side containers will fit in a standard rectangular MCC (allowing 2” extra on all four sides and 2” extra on top). Additional details on these 8.4 m3 soft-side containers are provided in Appendix H.

Figure F-17 Aerial View of Radioactive Waste Disposal Facilities at WCS

Figure F-18 Wastes being Loaded into Rectangular MCCs inside a Disposal Cell with Components of the Multi-Barrier Liner Visible in the Background (Note the scale of the disposal cell)

Waste Control Specialists is equipped to receive wastes by truck and by rail. For rail, they have a receiving building that straddles the railhead, and their own locomotive to bring wastes onsite from nearby Eunice, New Mexico.

F.5.2 Key Regulatory Requirements

Texas is a NRC Agreement State and the Texas Commission on Environmental Quality is responsible for licensing and inspecting the WCS radioactive and mixed waste disposal facilities. In August of 2004 WCS submitted an application for a radioactive materials license to build and operate their first LLW disposal facility. For licensing the FWF, the Texas Commission on Environmental Quality used their state regulations that are equivalent to the NRC's 10 CFR 61 licensing requirements.

After a detailed multi-year licensing process, the Texas Commission on Environmental Quality issued a Radioactive Materials License to WCS to dispose of LLW in 2009. A copy of the current License (Amendment number 31) is available at http://www.wcstexas.com/wp-content/uploads/2017/10/RML-R04100-Amendment-31.pdf.

Texas Commission on Environmental Quality approved major construction in 2011, and in 2012 the first radioactive wastes were received for disposal. The FWF is licensed to accept for disposal Class A, B and C LLW and Class A, B and C MLLW. Before disposal, all waste must meet LDR requirements in RCRA 40 CFR 268 (or state equivalent LRD requirements).

The FWF is licensed for up to 26,000,000 ft3 (~736,000 m3) and 5,600,000 curies total of wastes. *The licensed volume limit of the FWF is roughly twice the volume of the grouted SLAW* (Grout Case 2 volume is 367,900 m3). The FWF is designed to be built in 11 phases. Only the first phase of the eleven phases has been constructed, as shown in Figure F-17.

The term of the current license is through September 2024, with provision for 10-year renewals thereafter. The state of Texas takes ownership of LLWs disposed in the Compact Disposal Facility and the DOE has signed an Agreement to take ownership of the FWF after its closure. In post-closure, the DOE will be responsible for the immobilized SLAW, whether disposed onsite in the IDF or offsite at the WCS.

In addition to the License issued by the Texas Commission on Environmental Quality, WCS maintains other permits and licenses which are overviewed at http://www.wcstexas.com/facilities/licenses-permits/.

F.5.3 Waste Acceptance Criteria

As used here, WAC are the criteria the wastes must meet to be acceptable for disposal. The WAC for the FWF are included as an amendment to the Texas Commission on Environmental Quality license for the FWF, and these criteria are detailed in *WCS's Federal Waste Disposal Facility (FWF) Generator Handbook*, revision 4, issued 8-28-15. The purpose of this section is to highlight some of the WAC that may be relevant to disposal of the immobilized SLAW and the reader is directed of the *FWF Generators Handbook* for the full set of criteria (http://www.wcstexas.com/wp-content/uploads/2018/03/FederalCustomers.pdf).

There are many components to the WAC for the FWF, including: limits on free liquids (<1% of the volume of containerized waste), maximum void space requirements, transportation requirements and prohibited waste types. Prohibited wastes include such items as: high-level radioactive waste, waste capable of generating toxic gases (excluding radioactive gases), waste readily capable of detonation or of explosive decomposition or reaction at normal pressures and temperatures or of explosive reaction with water.

F.5.3.1 General Waste Packaging Requirements

Some of the general packaging requirements are:

- Each container shall only contain one approved profiled (characterized) waste stream
- Packages should weigh 10,000 lbs. (4,545 kg) or less, unless special arrangements have been made
- All containers transported on public roads to WCS are required to meet the applicable DOT regulations
- Except for bulk wastes and Large Components, waste packages must fit in a MCC.

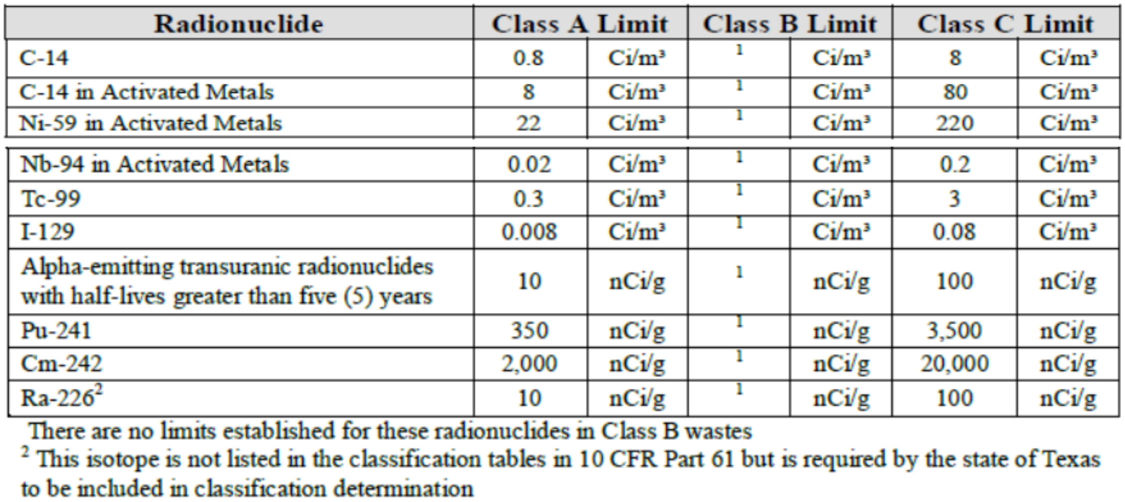
F.5.3.2 Land Disposal Restrictions

Waste disposed at WCS must comply with the LDRs detailed in 40 CFR Part 268. Land disposal restrictions that may apply to the immobilized SLAW, and strategies for complying with those LDRs, are provide in Appendix I, “Regulatory Compliance.”

F.5.3.3 Radiological Waste Acceptance Criteria

The radiological WAC for the FWF is based on the NRC's classification system which divides LLW into “classes” for disposal with Class A LLW being the least hazardous and with Greater-than-Class-C (GTCC) LLW being the most hazardous. The NRC describes these classes in 10 CFR 61.55. The FWF is licensed for disposal of Class A, Class B, and Class C (as defined in 30 TAC §336.362) LLW and MLLW and bulk Class A LLW and MLLW in reusable packages with a dose rates of <100 mrem/hr. at 30 centimeters (~1'). Two tables are provided by WCS for classifying wastes as Class A, B or C for disposal; GTCC wastes are currently prohibited. The two tables from the *FWF Generators Handbook* are copied and inserted here as Table F-24 for long-lived nuclides and Table F-25 for short lived nuclides.

Table F-24 Table I Class A and C Waste - Long Lived Isotopes.

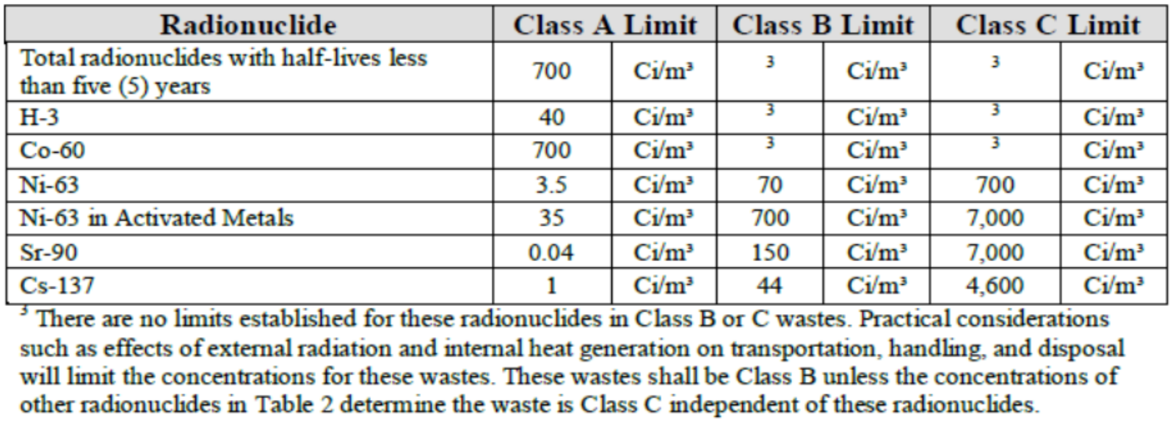


Radionuclide	Class A Limit		Class B Limit		Class C Limit	
C-14	0.8	Ci/m^3	[1]	Ci/m^3	8	Ci/m^3
C-14 in Activated Metals	8	Ci/m^3	[1]	Ci/m^3	80	Ci/m^3
Ni-59 in Activated Metals	22	Ci/m^3	[1]	Ci/m^3	220	Ci/m^3
Nb-94 in Activated Metals	0.02	Ci/m^3	[1]	Ci/m^3	0.2	Ci/m^3
Tc-99	0.3	Ci/m^3	[1]	Ci/m^3	3	Ci/m^3
I-129	0.008	Ci/m^3	[1]	Ci/m^3	0.08	Ci/m^3
Alpha-emitting transuranic radionuclides with half-lives greater than five (5) years	10	nCi/g	[1]	nCi/g	100	nCi/g
Pu-241	350	nCi/g	[1]	nCi/g	3,500	nCi/g
Cm-242	2,000	nCi/g	[1]	nCi/g	20,000	nCi/g
Ra-226[2]	10	nCi/g	[1]	nCi/g	100	nCi/g

There are no limits established for these radionuclides in Class B wastes

[2] This isotope is not listed in the classification tables in 10 CFR Part 61 but is required by the state of Texas to be included in classification determination

Table F-25 Table II Class A, B and C Waste - Short Lived Isotopes.



Radionuclide	Class A Limit		Class B Limit		Class C Limit	
Total radionuclides with half-lives less than five (5) years	700	Ci/m^3	[3]	Ci/m^3	[3]	Ci/m^3
H-3	40	Ci/m^3	[3]	Ci/m^3	[3]	Ci/m^3
Co-60	700	Ci/m^3	[3]	Ci/m^3	[3]	Ci/m^3
Ni-63	3.5	Ci/m^3	70	Ci/m^3	700	Ci/m^3
Ni-63 in Activated Metals	35	Ci/m^3	700	Ci/m^3	7,000	Ci/m^3
Sr-90	0.04	Ci/m^3	150	Ci/m^3	7,000	Ci/m^3
Cs-137	1	Ci/m^3	44	Ci/m^3	4,600	Ci/m^3

[3] There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes. These wastes shall be Class B unless the concentrations of other radionuclides in Table 2 determine the waste is Class C independent of these radionuclides.

F.5.4 Classification of Wasteforms for Disposal

Table I and Table II (reproduced as Tables F-24 and F-25) are used to classify wastes as Class A, B, C for disposal. Some points on the use of the Tables:

- The specific activity of each nuclide in the final WF must be known in Ci/m3, except for the transuranics and Ra-226, which must be known in nanoCi/gram
- Each limit is the full limit. For example, if C-14 is the only nuclide in the waste, and the concentration is 8 Ci/m3, the waste would be classified as Class C; any other Table I nuclide, or any additional amount of C-14 would cause the waste to be GTCC
- If there are multiple long-lived nuclides (Table I nuclides), then the fractional contribution of each nuclide must be calculated, and the sum of those fractional contributions must be less than 1 for a given class of waste. The use of the sum of fractions to determine waste classification is explained in 10 CFR 61.55(a)(7)
- If a waste contains long-lived Table I nuclides AND short-lived (Table II) nuclides: the WF will be classify based on the classification of the long-lived (Table I) nuclides, unless a higher classification is derived from the short-lived (Table II) nuclides.

Use of these Tables to classify wastes for disposal requires some experience.

F.5.4.1 Observations about the Radiological WAC and the Characteristics of the SLAW

Without classifying the final WFs, it is still possible to make some observations about the character of the SLAW, as compared to the radiological WAC:

1. Disposal of Tc-99 is not an issue at WCS: The Class C limit for Tc-99 is 3 Ci/m3, whereas the average concentration of Tc-99 in the Feed Vector is 0.05 Ci/m3 (roughly one one-hundredth the limit). The very highest concentration of Tc-99 in any one month is 0.6 Ci/m3, which is still well below the disposal limit. At WCS there is no groundwater pathway, or mechanism for erosion to expose the wastes to the public receptor, and therefore, the disposal limit for Tc-99 is solely to protect an inadvertent human intruder. As evidence of this, WCS's Class C concentration limit for Tc-99 (3 Ci/m3) is identical to the NRC's Table 1 concentration limits to protect an inadvertent human intruder from Tc-99 found in 10 CFR 61.55. At a disposal facility with a groundwater pathway, the disposal limit for Tc-99 might be smaller than 3 Ci/m3, to limit possible doses from the groundwater pathway to the public.
2. Disposal of I-129 is not an issue at WCS: The Class C limit for I-129 is 0.08 Ci/m3, whereas the average concentration of I-129 is in the Feed Vector is 0.00005 Ci/m3 (roughly one one-thousandth the limit). The very highest concentration of I-129 in any one month is 0.0002 Ci/m3, which is still well below the disposal limit. The basis for WCS's Class C limit for I-129 is the same as the basis for the Tc-99 limit, explained above.
3. The average concentration of Sr-90 in the Feed Vector (1.5 Ci/m3) is well above the Class A limit of 0.04 Ci/m3; therefore, the immobilized SLAW will not classify as Class A.
4. For a fixed inventory of transuranic nuclides, the low specific weight of the Steam Reforming Case 2 wastes (800 kg/m3 (50 lb/ft3)) will cause the concentrations of the transuranic nuclides (measured in nana-curies per gram) to double, as compared to the heavier Grout Case 2 wastes at 1770 kg/m3 (110 lb/ft3). Also, for a fixed inventory of nuclides, the lower volume increase (factor of 1.2) for the Steam Reformed Case 2 wastes will cause the concentrations of all nuclides to be higher than the concentrations from Grout Case 2, with its larger volume increase (factor of 1.8). For these two reasons, the Steam Reformed Case 2 wastes will have a higher classification than the Grout Case 2 WFs.

F.5.4.2 How to Use WCS's Radiological WAC to Classify Wasteforms

The calculations needed to classify the final WFs for disposal can be illustrated using one long-lived nuclide. For this illustration, Tc-99 and the Feed Vector data for the WTP-PT for April 2060 were chosen, along with information about the grout WF and WCS's Table I classification table:

- Table F-1 presents the radionuclide concentrations from the Feed Vector for the WPT PT for April 2060
- Grouting will increase volume of the Feed Vector by a factor of 1.8, which will decrease specific activities found in the Feed Vector by a factor of 0.56 (=1/1.8).
- The specific activity of Tc-99 in the Feed Vector (see Table F-1) is 8.90E-02 Ci/m3 and therefore, specific activity of Tc-99 in the Grout WF will be 4.94E-02 Ci/m3 (= 8.90E-02 x 0.56)
- The fractional activity of Tc-99 in grout for Table I Class C classification is 1.64E-02, which is derived by dividing the specific activity of the Tc-99 in the waste (4.94E-02 Ci/m3) by the Class C limit for Tc-99 (3 Ci/m3)
- The fractional contribution of each Table I long-lived nuclide can be calculated in this way. The fractional contribution of each nuclide is then added together, and if the sum of those fractions is less than 1 but greater than 0.1, the grout produced from the April 2060 WTP-PT feed will be Class C for long-lived nuclides
- Because there are short-lived Table II nuclides in the April 2060 feed, it is also necessary to calculate the classification of the short-lived nuclides using Table II criteria, in the same manner as above.
- Finally, the classification of the grout produced in April of 2060 from feed from the WTP-PT can be determined based on the Table I (long-lived) classification (Class C in this case), unless the Table II (short-lived) classification is higher. In this example, because the Table II (short-lived) classification is not higher than Class C, the final classification of the grout from the WTP-PT for April 2060 is Class C.

F.5.4.3 Classifying the Primary Wasteforms Using WCS's Radiological WAC

Information provided by the Feed Vector combined with information on the characteristics of the final WFs can be used to determine the classification (Class A, B, C or GTCC) of the final WF for each month that pretreated SLAW is produced by the WTP-PT and the LAWPS. Table F-26 presents the list of primary WFs being considered for disposal at the WCS FWF.

Table F-26 Nature and Volume of Primary WFs for Disposed at WCS.

Treatment Technology	**Container**	**Total Volume**	**Average Volume per month**	**Containers per month** (for 337 months)
Grout Case 2 with LDR pretreatment	8.4 m3 bag in reusable steel overpack	367,900 m3	1092 m3	130
Grout with LDR pretreatment & 99% Sr-90 removed (variant 2f)	8.4 m3 bag in reusable steel overpack	367,900 m3	1092 m3	130
Steam Reforming Case 2	8.4 m3 bag in reusable steel overpack	245,300 m3	728 m3	87

The Feed Vector data is contained in a large EXCEL Spreadsheet discussed in Section F.3.1. A companion EXCEL workbook has been setup: (1) that contains WCS's Table I and Table II radiological WAC for classifying wastes for disposal, (2) that accesses the Feed Vector data for every month of SLAW production, and (3) that utilizes the logic of calculating the sum of fractions and determining the waste classification (Class A, B, C or GTCC) from WCS's Table I and Table II WAC.

The EXCEL Workbook is also setup so that the Feed Vector concentrations can be modified to match the characteristics of the final WF. For example, the Workbook will decrease the specific activities of the nuclides to account for the volume increase caused by grouting and the Workbook uses the specific weight of the final WFs (e.g., 1770 kg/m3) to calculate the concentration of transuranics as nanoCuries per gram of waste.

The Feed Vector tracks eight alpha-emitting transuranic nuclides with half-lives greater than five years: Np-237, Pu-238, Pu-239, Pu-240, Am-241, Am-243, Cm-243 and Cm-244. In the Workbook, the concentration of these eight transuranic nuclides in the final WF are summed and compared to the 100 nCi/gram limit for transuranics.

The EXCEL Workbook was used to classify *all 441 discrete sets of monthly Feed Vector data* detailing the SLAW feed from the WTP-PT and LAWPS pretreatment facilities[106]. Table F-27 presents the categorization results.

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[106] If both pretreatment facilities (WTP-PT and LAWPS) operated every month over the 337 months, there would be 674 combined months of operations and 674 discrete sets of monthly Feed Vector data. However, neither facility operates full-time, *and there are 441 combined months of operations, with the associated 441 Feed Vector datasets for analysis.*

Table F-27 Classification of Primary Wasteforms for Disposed at WCS (measured as the number of months that SLAW is produced by WTP-PT and LAWPS).

Treatment Technology	Class A	Class B	Class C	GTCC
Grout Case 2 with LDR pretreat	0	408	33	0
Grout with LDR pretreat & 99% Sr-90 removed (variant 2f)	406	2	33	0
Steam Reforming Case 2	0	302	130	9

The clear majority of the primary Grout Case 2 WF will classify as Class B for disposal, with less than 10% classifying as Class C. This is not unexpected, as the average specific activity of Sr-90 in the Feed Vector (1.5 Ci/m3) is well above the Class A limit for Sr-90, and the specific activities of all nuclides in the Feed Vector are reduced by a factor of 1.8 and the final WF is relatively heavy (high specific weight). For a given inventory of transuranics, the greater the specific weight, the lower the concentration of transuranics, as measured as nanoCuries *per gram* of waste

With removal of 99% of the Sr-90, the Grout Case 2 WFs will classify as Class A, with less than 10% (33 months) remaining as Class C. It is the high concentration of the transuranics in feed from the WTP-PT is what keeps the 33 Feed Vector months from being Class A.

The majority of the primary WFs from Steam Reformed Case 2 will classify as Class B for disposal, with about 30% classifying as Class C. This is not unexpected, as the average specific activity of Sr-90 in the Feed Vector (1.5 Ci/m3) is well above the Class A limit for Sr-90, and the specific activities in the Feed Vector nuclides are only reduced by a factor of 1.2 and the final WF is relatively light (low specific weight). The light weight of the final WF doubles the concentration of the transuranics (as compared to grout).

Nine months of feed from the WTP-PT, when immobilized by Steam Reforming Case 2, will classify as GTCC MLLW. These nine months represent only 2% of the SLAW produced by the two pretreatment facilities over the 28 years. *The GTCC is exclusively from the summed transuranics in the SLAW from the WTP-PT,* and specifically for the months of December 2034 through March of 2035 and October 2035 through February of 2036.

Table F-28 presents detailed information on the nine months in which the Steam Reformed Case 2 mineral product would be classified as GTCC. If the sum of fractions from WCS's Table 1 Radiological WAC (Table F-28) is greater than 1, the WF will classify at GTCC, and if the sum of fractions is less than 1, then the WF will classify as Class C or Class A. Table F-28 presents an analysis in which Feed from the WTP-PT and LAWPS, for a given month, are combined prior to immobilization; the last column of Table F-28 shows the volume-weighted sum of fractions for the combined immobilized mineral product. The exception is that there is no Feed from LAWPS for December 2034 to down blend the Feed from WTP-PT for that month, and in this case the Feed for January 2034, February 2034 and December 2034 would need to be combined prior to immobilization. Even by combining the Feed from the WTP-PT with the LAW PS for a given month, there are still three months where the immobilized SLAW will be slightly above Class C and in those cases, Feed from adjacent months would be needed to keep the final product below the Class C limit (e.g., the Feed from WTP-PT and LAWPSs for March 2035 and October 2035 and November 2035 might all need to be combined to be below Class C). *Given the uncertainty in the Feed Vector data, it is not the intent of this analysis to fully map-out the blending – rather, this analysis in Table F-28 clearly demonstrates that local mixing can be used to prevent the generation of GTCC LLW.*

Table F-28 Calculation of Volume-Weighted, Table 1, Sum-of-Fractions for Steam Reformed Case 2

Date		WTP-PT Steam Reformed volume m3	**WTP-PT SOF for Table 1**	Volume weighted Table 1 SOF		LAWPS Steam Reformed volume m3	**LAWPS SOF Table 1**	Volume weighted Table 1 SOF		Volume WTP-PT+ LAWPS m3	**WTP-PT + LAWPS SOF for Table 1**
Jan 34		42	**0.44**	18		0					
Feb 34		183	**0.46**	84		0					
Dec-34		88	**1.38**	121		0				313*	**0.71***
Jan-35		1120	**1.31**	1467		374	**0.041**	15		1494	**0.99**
Feb-35		769	**1.25**	961		594	**0.041**	24		1363	**0.72**
Mar-35		977	**1.1**	1075		537	**0.040**	22		1514	**0.72**
Oct-35		919	**1.77**	1627		634	**0.096**	61		1553	**1.09**
Nov-35		813	**1.88**	1528		578	**0.097**	56		1391	**1.14**
Dec-35		796	**1.75**	1393		675	**0.098**	66		1471	**0.99**
Jan-36		868	**1.67**	1450		605	**0.098**	59		1473	**1.02**
Feb-36		881	**1.32**	1163		514	**0.098**	50		1395	**0.87**
	* Based on combined Feed from WTP-PT for Jan 34, Feb 34 and Dec 34										

F.5.4.4 Classifying Secondary Wasteforms using WCS's WAC

Three secondary WFs will be generated (1) during the immobilization of the primary WFs or (2) in a pretreatment process that operates before final immobilization. The three secondary WFs analyzed for possible disposal at the WCS are described below.

The process of immobilizing the primary WFs will generate operational wastes, such as contaminated HEPA air filters and granular activated carbon (GAC). These operational wastes with a radiological inventory will be managed as Solid Secondary Wastes (SSWs). Operational wastes, such as personal protective equipment, that are not anticipated to contain a significant radiological inventory will be managed onsite and are not discussed further.

The vitrification process will generate liquid secondary wastes that will be processed through the EMF and ETF, grouted and managed as solidified Liquid Secondary Wastes (LSW) for disposal.

In one variant case (2e2), the Tc-99 and I-129 will be selectively removed in pretreatment, prior to immobilization. In this 2e2 variant case, the primary WF will be grouted for onsite disposal in the IDF and the Tc-99 and I-129 will be grouted separately, and sent for offsite disposal at WCS as Pretreatment Waste (PW).

The volume and curie content of the solidified LSW and SSW are summarized in Table F-29 below. These volumes and curie contents are developed in Section F.3 in the discussion of the IDF. Assuming the Tc-99 and the I-129 are comingled in a single grouted WF, an analysis was undertaken to determine the waste classification for disposal at WCS based on WCS's WAC for long-lived nuclides.

Table F-29 Volume, Curie Content and Classification of Solidified LSW and SSW for Disposal at WCS.

	Vitrification	Steam	Grout
Solidified LSW			
Tc-99	0.061 Ci	NA	NA
I-129	0.022 Ci	NA	NA
Total volume	3803 m3	NA	NA
Classification	Class A	NA	NA
volume of LSW as % of volume of primary WF	4.7%	NA	NA
SSW (grouted HEPAs)			
Tc-99	7.8 Ci	7.8 Ci	0.78 Ci
I-129	0.075 Ci	0.075 Ci	0.01 Ci
Total volume	61 m3	61 m3	6 m3
Classification	Class A	Class A	Class A
SSW (grouted GAC)			
Tc-99	0	0	0
I-129	2.5 Ci	0.25 Ci	0.025 Ci
Total volume	555 m3	555 m3	56 m3
Classification	Class A	Class A	Class A
Volume grouted SSW (HEPA + GAC) as % of volume of primary WF	<1%	<1%	<1%

In all cases, the solidified LSW and the grouted SSWs will classify as Class A MLLW for disposal at WCS. Not only is the waste classification low, but the total volumes of the solidified LSW and SSWs are also low, when compared to the total volume of the respective primary WFs. The total volumes of these WFs are all less than 1% of the volume of the respective primary WFs, but for the solidified LSW from vitrification. Because of the low waste classifications and the comparatively small volumes of wastes, only the volume of the solidified LSW from vitrification is carried into the cost analysis for disposal and the offsite transportation analysis in Appendix G. Table F-29 summarizes information on the solidified LSW to be further assessed.

Pretreatment Waste - In variant 2e2, the Tc-99 and I-129 are selectively removed in pretreatment and disposed at WCS, while the primary WF is grouted for disposal in the IDF. For this disposal analysis, it is conservatively assumed that 99% of each nuclide is removed and will be shipped and disposed of in a grout wasteform. Removal of 99% of each nuclide may not be needed and may not be possible – but that is the bounding assumption used for this analysis. Based on statistics from the Feed Vector, there is a total of:

- 11,801 Ci of Tc-99 and
- 12.04 Ci of I-129 in the SLAW.

Given these total curie amounts, an analysis was undertaken to determine the volume of grout needed to immobilize the pretreatment wastes for shipping and disposal at WCS. It is further assumed that the Tc-99 and I-129 would be managed separately (not comingled), uniformly distributed in a grout matrix WF, and that the WFs would be shipped in high-weight-capacity B-25 boxes with an internal volume of 2.5 m3. It is assumed that the secondary wastes (LSW, SSW and PW) will not qualify for shipping as low-specific activity material and would be shipped in B-25 boxes containing less than the A_2 quantity per box. The A_2 quantity and shipping as low-specific activity material are discussed in detail in Appendix G. Table F-30 shows the limiting Class C limit for disposal at WCS and the limiting A_2 value for a volume of 2.5 m3 (discussed in detail in Appendix G).

Table F-30 Limiting Criteria for Shipping and Disposal of Tc-99 and I-129 (assuming 2.5 m3 shipping container).

	A_2 value for shipping	**WCS Class C limit for disposal**
Tc-99	24 Ci	3 Ci/m3
I-129	unlimited	0.08 Ci/m3

As shown in Table F-31, the Class C limit is the limiting criteria for both nuclides. Based on these limiting criteria and the total number of curies contained in the PW wastes (assuming 99% of total curies), Table F-31 presents the total volume of pretreatment wastes that would be generated, to be at the Class C limit. As shown, those volumes were then increased by 10%, because of the difficulties of generating wastes to exactly the Class C limit.

Table F-31 Volume of Class C Pretreatment Wastes (from 2e2).

	99% of Curies	**WCS Class C limit**	**Total Volume for Class C limit**	**Total Volume + 10%**	**Average Volume per Month** (337 months)
Tc-99	11,680	3 Ci/m3	3,890 m3	4,280 m3	13 m3
I-129	11.92	0.08 Ci/m3	150 m3	165 m3	0.5 m3

Because of the very small volume of PW containing I-129, only the volume of solidified PW containing Tc-99 is carried into the cost analysis for disposal and the offsite transportation analysis. *Table F-32 presents the volumes and classification of all Secondary Wastes to be carried forward for disposal costing and for offsite transportation analysis in Appendix H.*

Table F-32 Nature and Volume of all Secondary Wasteforms Carried Forward for Disposal Costing and Transportation Analysis.

	Total Volume	**Waste Classification**	**Average Volume per month**	**Average number B-25 boxes per month**
Solidified LSW from Vit (variant 1c is primary cannister Vit to IDF & secondary to WCS)	3,803 m3	Class A	12 m3	5
Pretreatment Waste containing Tc-99 (from variant 2e2)	4,280 m3	Class C	13 m3	5

F.5.5 Costs Considerations for Disposal

The ability to meet the WAC, the cost of transportation and the cost of disposal are important considerations in assessing an offsite disposal option. The ability of the WFs to meet the WAC, and the cost of disposal are addressed in this Appendix and Section 7, while transportation costs are discussed in Appendix H and Section 7.

Current prices for the DOE to dispose of MLLW at WCS are presented in an Indefinite Delivery/Indefinite Quantity contract between the DOE and WCS, under which Firm-Fixed-Price task orders can be issued. The contract is effective for April 12, 2018 through April 11, 2023. The prices in the Indefinite Delivery/Indefinite Quantity contract contain a premium, because of the difficulties of managing a large facility, in anticipation of indefinite quantities of wastes, to be delivered at indefinite dates. For this NDAA study, it is assumed that WCS would offer a 25% price cut, for a steady, anticipatable waste stream, and this study uses:

- $1370/m3 for Class A MLLW and
- $5220/m3 for the Class B and C MLLW.

The Class B and C MLLW disposal fees are identical, because these wastes are managed in the same manner onsite. There is a large cost differential between disposal of Class A MLLW and disposal of Class B and C MLLW, because disposal of Class A bulk wastes is easier and less expensive than disposal of Class B and C MLLW in MCCs. The disposal fees cover onsite disposal activities such as verifying paperwork, radiological surveying and unloading the waste packages from the railcar.

As shown in Table F-33, the disposal fees were used to calculate the disposal costs for Grout Case 2, Steam Reformed Case 2, the solidified LSW from Vitrification and the PW from variant 2e2. The disposal costs shown in Table F-33 are not the full cost of disposal, as wastes must be properly characterized, packaged and shipped to WCS. Many of these other costs are addressed in Appendix H.

Table F-33 Disposal Costs for Disposal of Grout Case 2, Steam Reformed Case 2, Solidified LSW from Vitrification and Pretreatment Waste Containing Tc-99.

Wasteform	**Total Volume**	**Class A**	**Class B**	**Class C**	**Disposal Costs**
Grout Case 2 with LDR pretreatment	367,900 m3	0	408 months	33 months	**$1.9 B***
Steam Reformed Case 2	245,300 m3	0	302 months	139 months	**$1.3 B***
Solidified LSW from Vit (from variant 1c)	3,803 m3	3,803 m3	0	0	**$0.0052 B**
Pretreatment Waste containing Tc-99 (from variant 2e2)	4,280 m	0	0	4,280 m3	**$0.022 B**
* because all wastes are Class B and C, the total volume of each WF was used to calculate the disposal cost (i.e., 367,900 m3 of grout and 245,300 m3 of steam reformed)					

F.5.6 Area for Further Analysis

Because of the ~ $4,000 per cubic meter cost differential between the disposal fee for Class A MLLW and the disposal fee for Class B/C MLLW disposal, analysis was undertaken to determine how much Sr-90 would have to be removed to change the classification of the final WFs from Class B/C to Class A, for a grouted WF. Results of the analysis are summarized in Table F-34.

Table F-34 Classification Grout with Strontium-90 Removal (measured as the combined number of months of output from WTP-PT and LAWPS)

% Sr-90 removal	**Class A (months)**	**Class B (months)**	**Class C (months)**	**GTCC (months)**	**Notes**
None	0	408	33	0	transuranics in SLAW from WTP-PT cause Class C
90% removal	70	338	33	0	transuranics in SLAW from WTP-PT cause Class C
95% removal	94	314	33	0	transuranics in SLAW from WTP-PT cause Class C
99% removal	406	2	33	0	transuranics in SLAW from WTP-PT cause Class C

As shown in Table F-34, almost all the grouted WF would be classified as Class A, if 99% of the Sr-90 could be removed prior to immobilization. With a total volume of 367,900 m3 (as grout) and a cost differential of ~$4,000 per m3 between Class A and Class B/C, *the cost savings in disposal fees would be roughly $1.5 B.* Additionally the Clive disposal facility in Utah could be considered, if the grouted or steam reformed WF classifies as Class A MLLW. The Clive facility is closer to Hanford (lower transportation costs), and the Clive facility would probably offer a competitive disposal fee for disposal of the Class A MLLW.

If additional funds were available, a study could be undertaken to determine the feasibility and cost of removing 99% of the Sr-90 in a pretreatment facility. If it is feasible to remove 99% of the Sr-90, then the cost to remove and dispose[107] of the Sr-90 could be compared to the cost savings in transportation and disposal fees.

Though a significant potential cost savings, (1) it may be very difficult to achieve 99% removal and (2) if a process did provide 99% removal, a new capital project would need to be designed, funded, built and operated at substantially less than $54 M per year ($1.5 B divided by 28 years).

F.5.7 Key Conclusion from Analysis of Disposal at WCS

The key take-away from this long and detailed analysis is that all final WFs (Grout Case 2 and Steam Reforming Case 2 and all analyzed secondary WFs) can be accepted for disposal at the WCS disposal facility (assuming LDR issues are addressed).

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[107] Once removed, the Sr-90 could be sent to WCS for disposal as a separate WF, as the Class C limit for Sr-90 disposal at WCS is quite high (7,000 Ci/m3).

APPENDIX G. TRANSPORTATION

G.1 INTRODUCTION

This appendix describes the programs that will be needed to transport the primary Grout Case 2 and Steam Reformed Case 2 wasteforms (WFs) and secondary WFs from the Hanford Reservation to the WCS disposal facilities in west Texas. This appendix addresses the following topics:

- General evaluation assumptions and approach
- Key regulatory considerations for packaging and transportation
- Nature and volume of wastes to be shipped
- Lag storage facility
- Low-specific activity determination and package requirements
- Technology Readiness Level
- Routing and program to transport waste to WCS by rail
- Costs
- Technical risks
- Programmatic risks
- Areas for further analysis
- Conclusions.

G.2 GENERAL EVALUATION ASSUMPTIONS AND APPROACH

For this analysis, current conditions are assumed to prevail. This means that the analysis is based on the current railroads, the current regulatory requirements for shipping and the current shipping and packaging technologies.

Basing the analyses on current conditions prevents undue speculation about future conditions, while allowing an even-handed comparison of disposal of primary and second wastes at the IDF and the WCS disposal facilities. Where additional capacity might be needed, it is assumed that the additional capacity could be created within the existing infrastructure and at a similar cost.

G.3 KEY REGULATORY CONSIDERAITONS

The U.S. Nuclear Regulatory Commission (NRC) *regulates the packaging* for the transport of radioactive materials. The U.S. Department of Transportation (DOT) coordinates with the U.S. NRC to set rules for the packaging. The DOT also works with the NRC and affected States *to regulator their transport*.

G.3.1 10 CFR 71 Packaging and Transportation of Radioactive Material

The NRC's 10 Code of Federal Regulations (CFR) 71 governs the "Packaging and Transportation of Radioactive Material." This regulation defines the packaging and transportation performance criteria to ensure the safe transport of radioactive materials under normal and hypothetical accident conditions.

The NRC's regulation uses a graded approach in setting packaging criteria, to protect public health and the environment where:

- "Low specific activity" (LSA),[108] materials may be shipped in industrial packages (IPs) that are exempt from NRC package certification (but not exempt from DOT requirements)

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[108] Low Specific Activity material means radioactive material with limited specific activity that is nonfissile or is excepted

- Materials that exceed the LSA limits, but are below the "A_2" content limit[109], must be shipped in Type A packaging, and where
- Higher-activity content materials that exceed the LSA limits, and that exceed the A_2 content limit, must be shipped in Type B packaging, which meets the most stringent criteria (except for the air-transport criteria).

All packages for shipping radioactive material (IP or Type A or Type B) must be designed and prepared so that under conditions normally incident to transportation, the radiation level does not exceed 2 millisievert/hour (200 millirem/hour) at any point on the external surface of the package, and the transport index[110] does not exceed 10. (10 CFR 71.47)

It is not anticipated that any of the SLAW WFs will need to be transported in a Type B shipping cask. Shipping in Type A containers and IPs is addressed below.

G.3.1.1 Shipping in Type A Containers

The maximum amount of radioactive material that can be carried in a Type A container depends on the *form of the material* and the *summed radiological content*. The NRC defines two forms of material in Part 71, "special form" and "normal form." In simple terms, normal form materials are dispersible in a transportation accident, and special form materials are not dispersible. Special form radioactive material means radioactive material that (1) is either a single solid piece or is contained in a sealed capsule that can be opened only by destroying the capsule, (2) has a certain minimum size and (3) it satisfies the rigorous requirements of 10 CFR 71.75. Special form materials are not easily dispersible. If a material is not special form, then the material is normal form. Sealed radioactive sources are an example of special form material. Most radioactive materials are normal form.

The methodology and tables for determining if the amount of activity in a container exceeds the A_2 limit are presented in Appendix A of 10 CFR 71.

G.3.1.2 Shipping in Industrial Packages

"Low specific activity" radioactive materials may be shipped as NRC-defined LSA material in IPs that are exempt from NRC certification, if the specific activity (the activity per unit mass) of the WFs is low enough, and other requirements are met. As discussed later, the LSA criteria are linked to the A_2 quantity. The three types of LSA materials and requirements that IPS must meet are discussed in detail in Section G.7.

G.3.2 49 CFR 171-173 Hazardous Materials Regulations

The U.S. DOT's 49 CFR 171-173 address many facets of the transport of radioactive materials, which are a subset of the DOT's broader definition of "Hazardous Materials." Each licensee who transports licensed material on

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under 10 CFR 71.15, and satisfies the descriptions and limits for LSA-I, LSA-II, and LSA-III materials set forth in 10 CFR 71.4. Shielding materials surrounding the LSA material may not be considered in determining the estimated average specific activity of the package contents. (10 CFR 71.4).

[109] The A_2 value is the maximum amount of radioactive material (measured in becquerels or curies), other than special form, LSA, and Surface Contaminated Object materials, permitted in a Type A package. This value is either listed in 10 CFR Part 71, Appendix A, Table A-1, or may be derived in accordance with the procedures prescribed in 10 CFR Part 71, Appendix A. (10 CFR 71.4)

[110] The transport index is the number determined by multiplying the maximum radiation level in millisievert (mSv) per hour at 1 meter (3.3 ft) from the external surface of the package by 100 (equivalent to the maximum radiation level in millirem per hour at 1 meter (3.3 ft)).

public highways, or who delivers licensed material to a carrier for transport, must comply with the applicable requirements of the DOT regulations in 49 CFR. Some of the activities regulated by 49 CFR 171-173 include:
- Packaging - 49 CFR part 173: subparts A, B, and I
- Marking and labeling - 49 CFR part 172: subpart D; and §§ 172.400 through 172.407 and §§ 172.436 through 172.441 of subpart E
- Placarding - 49 CFR part 172: subpart F, especially §§ 172.500 through 172.519 and 172.556; and appendices B and C
- Accident reporting - 49 CFR part 171: §§ 171.15 and 171.16
- Shipping papers and emergency information - 49 CFR part 172: subparts C and G
- Hazardous material employee training - 49 CFR part 172: subpart H
- Security plans - 49 CFR part 172: subpart I
- Hazardous material shipper/carrier registration - 49 CFR part 107: subpart G, and
- DOT regulations specific to transport by rail include 49 CFR part 174: subparts A through D and K.

The DOT regulations also define "contamination," which means the presence of a radioactive substance on a surface in quantities in excess of 0.4 Becquerels per square centimeter (Bq/cm2) for beta and gamma emitters and low toxicity alpha emitters or 0.04 Bq/cm2 for all other alpha emitters. There are two categories of contamination:
(1) Fixed contamination means contamination that cannot be removed from a surface during normal conditions of transport.
(2) Non-fixed contamination means contamination that can be removed from a surface during normal conditions of transport. (49 CFR 173.443).

To ensure the appropriate scoping and costing, this study will rely on analogue costs from other programs, where the DOE has shipped radioactive wastes for disposal (e.g., shipping contaminated soils by rail for disposal). In this way, the scope and cost of meeting the above requirements above will be captured, without summarizing the large number of safety requirements found in 49 CFR 171-173 for shipping radioactive materials.

G.3.4 DOE Regulations and Orders

The DOE's Office of Packaging and Transportation provides packaging and transportation services to the entire DOE complex. The Atomic Energy Act of 1954, as amended, gives DOE broad authorities to regulate all aspects of activities involving radioactive material that are undertaken by DOE or on its behalf, including transportation. Authorities for the Office of Packaging and Transportation flow from 41 CFR 109-40, Transportation and Traffic Management, and 49 CFR 173, DOT, Shippers – General Requirements for Shipments and Packagings, which establishes DOE's transportation management and packaging certification authorities, and DOE Orders 460.1, Packaging and Transportation Safety, DOE Order 460.2, Departmental Materials and Transportation Management, and DOE Manual 460.2-1, Radioactive Material Transportation Practices Manual. DOE Order 460.1 establishes safety requirements for the proper packaging and transportation of offsite shipments and onsite transfers of hazardous materials, including radioactive materials. DOE Order 460.2 establishes standard transportation practices for DOE elements to use in planning and executing offsite shipments of radioactive material including radioactive waste.

DOE Manual 460.2-1 was developed through a collaborative effort under the Senior Executive Transportation Forum (established by the Secretary of Energy in January 1998) to coordinate efforts of Departmental elements involved in the safe transportation of radioactive material and waste. Subsequent updates also reflect the continuing collaboration of DOE and outside organizations such as the Tribal Caucus and State Regional Groups, on transportation of radioactive material and waste. The Manual is composed of transportation practices that establish a standardized process and framework to include interacting with State, Tribal, and local authorities, other Federal agencies, and transportation contractors and carriers regarding DOE radioactive material shipments.

G.3.5 National Environmental Policy Act

Actual implementation of a large-scale, offsite disposal program, with the associated transportation program, such as outlined here in Appendix G, would probably require the development of an Environmental Impact Statement (EIS).

This NADA study is not an EIS, and the technical risks from the proposed shipping program are discussed in Section G.10.

G.4 NATURE AND VOLUME OF WASTES TO BE SHIPPED

The nature and volume of the wastes to shipped are described in Appendix F, "Disposal," and are summarized in Table G-1 below. As discussed in Appendix F, the primary wasteforms will be shipped in 8.4 m3 containers, and the secondary wastes will be shipped in B-25 boxes that meet Type A standards.

Table G-1. Nature and Volume of Wastes to be Shipped to WCS

	Container	**Total Volume and Average Volume/ month**	**Average Containers/month** for 337 months
Primary Wastes			
Grout Case 2 with LDR pretreatment	8.4 m3 bag in reusable steel overpack	367,900 m3 and 1092 m3/month	130
Grout with LDR pretreatment & 99% Sr-90 removed (variant 2f)	8.4 m3 bag in reusable steel overpack	367,900 m3 and 1092 m3/month	130
Steam Reforming Case 2	8.4 m3 bag in reusable steel overpack	245,300 m3 and 728 m3/month	87
Secondary Wastes			
Solidified Liquid Secondary Wastes from Vit (primary canister Vit to IDF & secondary to WCS)	B-25 box	3,803 m3 and 12 m3/month	5
Pretreatment Waste containing Tc-99 (from variant 2e2)	B-25 box	4,280 m3 and 13 m3/month	6

G.5 ONSITE IMPACTS OF OUT-OF-STATE SHIPMENT

It is assumed that a rail spur to the Hanford site is maintained to allow rail transport of containerized waste. In addition, temporary onsite storage for staging containerized waste is required. It is assumed that the size of this facility would be limited and that the design of the facility would mitigate impacts of any postulated accident events during container handling. Accumulation of a large inventory of containerized SLAW is not assumed; i. e., a mid-term storage facility as required for HLW will not be constructed for SLAW. The SLAW lag storage facility would be designed to hold 2 months of production.

G.6 LOW-SPECIFIC ACTIVITY DETERMINATION AND PACKAGE REQUIREMENTS

As noted earlier, the NRC utilizes a graded approach in setting packaging and shipping requirements for the transport of radioactive materials. The least hazardous category of materials comprises those materials that qualify as Low Specific Activity (LSA). LSA material is radioactive material with limited specific activity that is nonfissile or is excepted under 10 CFR 71.15 and that satisfies the descriptions and limits for LSA set forth in 10 CFR 71.4. The NRC defines three categories of LSA materials: LSA-I, LSA-II and LSA-III. Working in tandem with the NRC, the DOT defines the packaging requirements for transporting these materials. Below is an overview of the three categories of LSA and their classification requirements.

LSA-I includes such materials as uranium and thorium ores, solid unirradiated natural uranium or depleted uranium or natural thorium, radioactive material for which the A_2 value is unlimited; or other radioactive material in which the activity is distributed throughout and the estimated average specific activity does not exceed 30 times the value for exempt material activity concentration determined in accordance with Appendix A of 10 CFR 71.

LSA-II includes other material in which the activity is distributed throughout and the **average specific activity is less than 10^{-4} A_2/gram for solids** and gases, and 10^{-5} A_2/gram for liquids

LSA-III includes solids (e.g., consolidated wastes, activated materials), *excluding powders*, which satisfy the requirements of § 71.77, in which:

(i) The radioactive material is distributed throughout a solid or a collection of solid objects, or is essentially uniformly distributed in a solid compact binding agent *(such as concrete,* bitumen, ceramic, etc.);

(ii) The radioactive material is relatively insoluble, or it is intrinsically contained in a relatively insoluble material, so that even under loss of packaging, the loss of radioactive material per package by leaching, when placed in normal pH water for 7 days, would not exceed 0.1 A_2 (see 10 CFR 71.77 for additional details); and

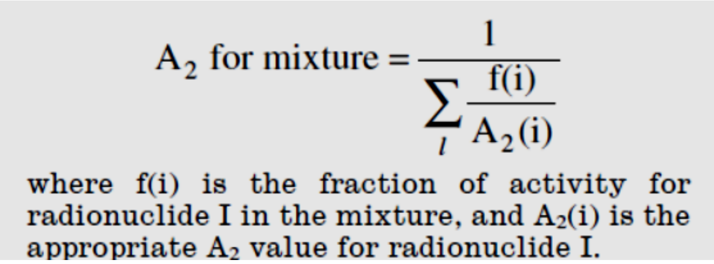
(iii) The estimated **average specific activity of the solid is less than 2×10^{-3} A_2/gram**." (10 CFR 71.4)

Other criterial that the three categories of LSA materials must meet include:

- External radiation at any point on the external surface of the shipping package must not exceed 2 mSv/h (200 mrem/h) (10 CFR 71.47(a))
- The material must have an external radiation dose less than or equal to 10 mSv/hour (1 rem/hour) at a distance of 3 m (10 ft) from the unshielded material (10 CFR71.14(b)(3)(i)) and 49 CFR 173.427)

Calculating the A_2 Value for a Mixture of Radionuclides

The A_2 of a material must be determined to determine whether a material meets the concentration limits for shipping as an LSA material. The formula for calculating the A_2 for a mixture of radionuclides is presented in Figure G-1, which is copied from the NRC's Appendix A of 10 CFR 71.



$$A_2 \text{ for mixture} = \frac{1}{\sum_{l} \frac{f(i)}{A_2(i)}}$$

where f(i) is the fraction of activity for radionuclide I in the mixture, and $A_2(i)$ is the appropriate A_2 value for radionuclide I.

Figure G-1 Formula for Calculating the A2 for a Mixture of Radionuclides

As a potentially bounding assessment of the A_2 value for the SLAW, the calculation was performed on the mixture of radionuclides from the month with the very highest Sum of Fractions for the long-lived nuclides for waste classification at WCS. From the EXCEL Workbook for classifying SLAW wasteforms for disposal at WCS, it was determined that SLAW from the WTP PT for November 2035 had the very highest sum of fractions. The A_2 calculation for wastes from November 2035 is presented in Table G-2.

Note in Table G-2, that for this waste stream, almost 90% of the activity is from just two nuclides: Sr-90 and Samarium-151 (Sm-151). The contribution of these two nuclides varies with the month and with source (WTP-PT and LAW PS), but in general Sr-90 and Sm-151 are major contributors to the activity in the SLAW. Appendix F contains a table that presents the *average radiological content* of all the combined SLAW from the WPTP-T and LAWPS for the 28 years of operations. As shown in the table in Appendix F, on average, Sr-90, is responsible for 81% of the total activity and Sm-151 is responsible for approximately 12% of the total activity. Both these nuclides have moderate half-lives (29 years and 88 years, respectively), and both are beta-emitters.

Table G-2. A_2 Calculation using Feed Vector Concentrations for SLAW from November 2035 from WTP PT

Symbol	**Element**	**A_2 (Ci)** from Apx A 10 CFR 71		Concentration (Ci/m3) from Feed Vector	fraction contribution f(i)	**f(i)/A_2(i)**
Ac-227 (a)	Actinium	2.40E-03		6.24E-06	1.53E-06	6.39E-04
Am-241	Americium	2.70E-02		1.71E-01	4.20E-02	1.56E+00
Am-243 (a)		2.70E-02		6.02E-05	1.479E-05	5.48E-04
C-14	Carbon	81		3.77E-03	9.26E-04	1.14E-05
Cd-113m	Cadmium	14		2.75E-03	6.76E-04	4.83E-05
Cm-242	Curium	0.27		6.11E-05	1.501E-05	5.56E-05
Cm-243		2.70E-02		3.04E-06	7.47E-07	2.77E-05
Cm-244		5.40E-02		4.85E-05	1.191E-05	2.21E-04
Co-60	Cobalt	11		7.69E-05	1.889E-05	1.72E-06
Cs-134	Cesium	19		4.26E-10	1.047E-10	5.51E-12
Cs-137 (a)		16		4.31E-02	0.0105879	6.62E-04
Eu-152	Europium	27		9.85E-05	2.42E-05	8.96E-07
Eu-154		16		1.89E-03	4.64E-04	2.90E-05
Eu-155		81		2.86E-04	7.03E-05	8.67E-07
I-129	Iodine	Unlimited		1.44E-04	3.54E-05	0.00E+00
Nb-93m	Niobium	810		1.02E-02	2.51E-03	3.09E-06
Ni-59	Nickel	Unlimited		4.50E-04	1.11E-04	0.00E+00
Ni-63		810		2.39E-02	5.87E-03	7.25E-06
Np-237	Neptunium	5.40E-02		1.45E-04	3.562E-05	6.60E-04
Pa-231	Protactinium	1.10E-02		9.71E-06	2.385E-06	2.17E-04
Pu-238	Plutonium	2.70E-02		3.28E-04	8.058E-05	2.98E-03
Pu-239		2.70E-02		3.81E-03	0.000936	3.47E-02
Pu-240		2.70E-02		9.70E-04	0.0002383	8.83E-03
Pu-241 (a)		1.6		4.15E-03	0.0010195	6.37E-04
Pu-242		2.70E-02		2.54E-07	6.24E-08	2.31E-06
Ra-226 (a)	Radium	8.10E-02		2.32E-08	5.699E-09	7.04E-08

Symbol	**Element**	**A_2 (Ci)** from Apx A 10 CFR 71		Concentration (Ci/m3) from Feed Vector	fraction contribution f(i)	**f(i)/A_2(i)**
Ra-228 (a)		0.54		6.06E-07	1.489E-07	2.76E-07
Ru-106 (a)	Ruthenium	5.4		7.91E-13	1.943E-13	3.60E-14
Sb-125	Antimony	27		3.93E-05	9.654E-06	3.58E-07
Se-79	Selenium	54		2.05E-03	0.0005036	9.33E-06
Sm-151	Samarium	270		1.44	0.3537473	1.31E-03
Sn-126 (a)	Tin	11		3.85E-03	0.0009458	8.60E-05
Sr-90 (a)	Strontium	8.1		2.21E+00	0.5429038	6.70E-02
T(H-3)	Tritium (1)	1100		8.26E-04	0.0002029	1.84E-07
Tc-99	Technetium	24		1.36E-01	0.0334095	1.39E-03
Th-229	Thorium	1.40E-02		2.12E-07	5.208E-08	3.72E-06
Th-232		Unlimited		5.94E-07	1.459E-07	0.00E+00
U-232 (medium lung absorption) (e)		0.19		4.63E-07	1.137E-07	5.99E-07
U-233 (medium lung absorption) (e)		0.54		1.61E-05	3.955E-06	7.32E-06
U-234 (medium lung absorption) (e)		0.54		3.25E-05	7.984E-06	1.48E-05
U-235 (all lung absorption types) (a), (d), (e), (f)		Unlimited		1.30E-06	3.194E-07	0.00E+00
U-236 (medium lung absorption) (e)		0.54		2.13E-06	5.233E-07	9.69E-07
U-238 (all lung absorption types) (d), (e), (f)		Unlimited		2.62E-05	6.436E-06	0.00E+00
Zr-93	Zirconium	Unlimited		1.06E-02	0.002604	0.00E+00
		Sum Ci/m3 =		4.07E+00	1.00E+00	
			Sum f(i)/A_2(i) =			1.68E+00
				A_2 for mix (Ci) =		**5.97E-01**

In the example above, the A_2 for the mixture is 0.597 curies and there are 4.07 curies in each cubic meter. Because Sr-90 and Sm-151 are such large contributors to the total activity, a test case was run assuming 99% of the Sr-90 and 100% of the Sm-151 are removed; and in this case the A_2 is 8.29E-02 curies and there are 0.54 curies in each m3. With the A_2 value of the mixture, it is possible to determine if a specific WF meets the concentration limits for shipping as an LSA material.

Classifying the Grout Wasteform as LSA-III

The criteria for classifying a material as LSA-III specifically mentions concrete WFs, and the Grout Case 2 WF may be shipped as LSA-III if the specific activity of the WF is low enough and the other LSA-III criteria are met. This analysis focuses on the specific activity criteria, and other criteria are discussed qualitatively.

For the SLAW from the WTP PT for November 2035, the summed activity is 4.07 Ci/m3 (Table G-2). With an activity multiplier of 0.56 (=1/1.8) for Grout Case 2 and a specific density of 1770 kg/m3 (see Table F-6), the specific activity of the Grout Case 2 is 1.2E-06 Ci/gram (= (4.07 x 0.56) / 1770,000).

For the SLAW from the WTP PT for November 2035, the A_2 is 0.597 (Table G-2) and the LSA-III criteria is 2×10^{-3} of the A_2/gram or 1.19E-03 Ci/gram. **Therefore, the specific activity of the Grout Case 2 WF easily meets the specific activity criteria for shipping as LSA-III** and specifically the WF is approximately 3 orders of magnitude less than the criteria for the November 2035 SLAW from the WTP PT. Because the radionuclide concentrations in Grout Case 2 for this month are almost 3 orders of magnitude lower than the LSA criteria, and because this analysis was run using the monthly output with the highest sum of fractions for the transuranics (and one of the highest total curie contents of any month), there is confidence that all the Grout Case 2 WFs can be shipped at LSA-III material.

Other criteria for LSA-III:

- The radiation dose on the external surface of the shipping package must not exceed 2 mSv/h (200 mrem/h), and the dose must be less than or equal to 10 mSv/hour (1 rem/hour) at a distance of 3 m (10 ft) from the unshielded material. Because the grout is self-shielding, and because the grout has a maximum of ~2 Ci/m3 of activity and because Sr-90 (a beta emitter) is 50% to 80% of those curies, it is assumed the grout would easily meet both dose-based criteria. If additional funding were available, Microshield calculations could be done in the future to confirm this assumption.
- Another criterion for classification as LSA-III is that the radioactivity be uniformly distributed in a solid compact binding agent (such as concrete, bitumen, ceramic). Because of the process of mixing the liquid SLAW with the dry ingredients, the Grout Case 2 WF will meet this criterion.
- The radioactive material is relatively insoluble, or it is intrinsically contained in a relatively insoluble material, so that even under loss of packaging, the loss of radioactive material per package by leaching, when placed in normal pH water for 7 days, would not exceed 0.1 A_2. It is assumed that the large monolith of grout, with a limited surface area, limited activity, and a high pH would meet this criterion. If additional funding were available, analysis can be conducted to validate this assumption.

Classifying the Steam Reformed Case 2 Granular Wasteform as LSA-II

The criteria for shipping as LSA-III material specifically excludes "powders," which excludes the steam reformed granular mineral product from being classified as LSA-III. However, the Steam Reformed Case 2 granular WF may be shipped as LSA-II if the specific activity of the WF is low enough and other LSA-II criteria are met. The analysis below focuses on the LSA-II criteria for specific activity, and other LSA-II criteria are discussed qualitatively. Note that the specific activity criteria for LSA-II is an order of magnitude stricter ($< 10^{-4}$ A_2/gram) than the criteria for LSA-III classification.

For the SLAW from the WTP PT for November 2035, the summed activity is 4.07 Ci/m3 (Table G-2). With a curie multiplier of 0.83 (=1/1.2) for the Steam Reformed Case 2 granular WF, and a specific density of 800 kg/m3 (see Table F-7), the specific activity of the Steam Reformed Case 2 granular WF is 4.2E-06 Ci/gram (= (4.07 x 0.83) / 800,000). For the SLAW from the WTP PT for November 2035, the A_2 is 0.597 (Table G-2) and 10^{-4} of the A_2/gram is 5.97E-05 Ci/gram. **Therefore, the specific activity of the Steam Reformed Case 2 granular WF meets the specific activity criteria for shipping as LSA-II,** and specifically the WF is approximately one order of magnitude less than the criteria for wastes from November 2035.

An analysis was also completed using a synthetic radiological profile composed of the very highest radionuclide concentration of each of the 47 nuclides tracked in the Feed Vector, and using these parameters, the Steam Reformed Case 2 WF also meets the LSA II criteria. Based on the analysis using the highest concentration of each nuclide and the analysis of the Feed from the WTP PT for November 2035, there is confidence that all the Steam Reformed Case 2 WFs can be shipped at LSA-II material.

Other criteria for LSA-II:

- The dose at the external surface of the shipping package must not exceed 2 mSv/h (200 mrem/h), and the radiation dose of the WF must be less than or equal to 10 mSv/hour (1 rem/hour) at a distance of 3 m (10 ft) from the unshielded material. Because of the self-shielding, and because the steamer reformed wasteform has a maximum of ~3 Ci/m3 of activity and because Sr-90 (a beta emitter) is 50% to 80% of those curies, it is assumed the steam reformed wasteform would meet both dose-based criteria. If additional funding were available, Microshield calculations could be done in the future to confirm this assumption.
- Another LSA-Ii criterion is that the radioactivity be uniformly distributed in the WF. Because of the immobilization process in the fluidized steam bed, the Steam Reformed WF will meet this criterion.

G.6.2 Package Requirements for Shipping LSA-II and LSA-III Materials

The DOT requires that LSA materials be transported in packages meeting Type IP-1, Type IP-2 or Type IP-3 packaging criteria (49 CFR 173.411). In Table 6 in 49 CFR 173.427, the DOT defines packaging requirements for all types of LSA materials, including the following requirements:

- LSA-II solid materials must be shipped in packages meeting Type IP-2 criteria for both “exclusive” and “non-exclusive” use shipments
- LSA-III solid materials must be shipped in packages meeting Type IP-2 criteria for exclusive use shipments and Type IP-3 criteria for non-exclusive use shipments.

For exclusive use, both LSA-II and LSA-III materials must be shipped in packages meeting Type IP-2 criteria, which in turn must meet the *general design requirements* of 49 CFR 173.410, and when subjected to the *tests specified in 49 CFR 73.465 (c) (free drop test) and (d) (stacking test)* must prevent the (i) loss or dispersal of the radioactive contents, and (ii) a significant increase in the radiation levels.

One of the tests, the stacking test, requires that Type IP-2 packages must be able to sustain a compressive load equal to five times the maximum weight of the package for 24 hours without the loss or dispersal of the radioactive contents (49 CFR 173.465 (d)).

For shipping non-combustible LSA-II and LSA-III solids, there is no limit to the amount of activity in any single conveyance (Table 5 in 49 CFR 173.427).

Soft Side Container

Figure G-2 shows an example of a large soft side container that can be used to ship LSA materials. For shipping and disposal at WCS, soft side containers with a capacity of 8.4 m3 will be used. The final, filled dimensions of each soft side will be: 110 inches L x 88 inches W x 53 inches H (filled volume will be 8.4 m3, which will half-fill a Modular Concrete Cannister at WCS).

Figure G-2 Example of Soft Side Container for Shipping LSA Materials (photograph from PacTec, Inc literature[111])

Reusable Steel Overpacks for Shipping

To facilitate handling and to provide a rigid form for filling the soft-site containers with grout or steam reformed mineral product, the IP-2 soft side containers will be managed in reusable steel overpacks (boxes). To do this, the soft side container will be placed in the overpack, filled with grout or steam reformed mineral product, transferred to a gondola railcar, secured, shipped to WCS; where the soft side will be off-loaded for disposal. The steel overpack is not required to meet DOT packaging requirements. The reusable overpack will then be transported back to Hanford for reuse. Conceptually, the steel overpack might look like the steel boxes shown in Figure G-3, but lighter weight and with a shallower lid. Finally, Figure G-4 shows an example of a 2.5 m3 B-25 box which will be used to transport the secondary solid wastes and the pretreatment wastes.

Figure G-3 Example of a Reusable Steel Split-Cavity Overpack (actual overpack would be smaller, lighter, and with a shallower lid) (photograph from Container Technologies Industries, LLC literature[112])

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[111] https://www.pactecinc.com/products/llmw-flexible-packaging

[112] http://www.containertechnologies.com/

Figure G-4 Example of B-25 Box (photograph from Container Technologies Industries, LLC literature)

G.7 TECHNOLOGY READINESS LEVEL

Facts presented in *DOE's Office of Packaging and Transportation Annual Report for FY 2016* provides strong evidence that the TRL is "high" for shipping immobilized SLAW from Richland to WCS. Their Annual report is available at: https://www.energy.gov/em/downloads/office-packaging-and-transportation-annual-report-fy-2016. The 2016 Report is the most current report available. Accomplishments of the Office of Packaging and Transportation in Fiscal Year 2016 included: performing four Motor Carrier Evaluation Program evaluations on motor carriers involved in transporting the DOE's "hazardous materials" and providing 138 Transportation Emergency Preparedness Program courses in 17 states to train more than 2,900 first responders. "Hazardous materials" is a broad regulatory category that includes Class 7 radioactive materials.

In Fiscal Year 2016 the DOE completed more than 8,400 offsite hazardous material shipments over public roads and railroads totaling more than 4.2 million miles with no recordable packaging and transportation accidents. Shipments by rail accounted for 4,260 of the 8,400 shipments (~ one-half of all the shipments); and the mileage by rail was over 135,000 miles. Equally important, 84% of all hazardous materials shipments were of LLW and MLLW; strong evidence that the TRL for shipping immobilized SLAW is high.

G.8 ROUTING AND PROGRAM TO TRANSPORT WASTE TO WCS BY RAIL

All wastes will be shipped on gondola railcars. Table G-3 summarizes the number of containers per gondola railcar for each WF, based on a cargo capacity of 200,000 lb per gondola railcar. Table G-4 summarizes the number of gondola railcars needed each month to transport the average monthly amount of each WF.

Table G-3 Calculating Number Containers per Gondola Railcar Based on 200,000 Pound Cargo Limit

	Specific Weight Wasteform	**Container Size**	**Weight per Container + 10%**	**Containers per Gondola**
Primary Wastes				
Grout Case 2 with LDR pretreatment	1770 kg/m3 (110 lb/ft3)	8.4 m3	16,350 kg ~ 36,000 lb	5
Grout with LDR pretreatment & 99% Sr-90 removed (variant 2f)	1770 kg/m3 (110 lb/ft3)	8.4 m3	16,350 kg ~ 36,000 lb	5
Steam Reforming Case 2	800 kg/m3 (50 lb/ft3)	8.4 m3	7,392 kg 16,260 lb	12

	Specific Weight Wasteform	Container Size	Weight per Container + 10%	Containers per Gondola
Secondary Wastes				
Solidified Liquid Secondary Wastes from Vit (primary Vit to IDF & secondary to WCS)	1770 kg/m3 (110 lb/ft3)	2.5 m3	4,868 kg 10,700 lb	18
Pretreatment Waste containing Tc-99 (variant 2e2)	1770 kg/m3 (110 lb/ft3)	2.5 m3	4,868 kg 10,700 lb	18

Table G-4 Calculating Average Number of Gondola Railcars per Month

	Average Volume per Month	Container Size	Average Containers per Month	Average Number Gondola Railcars per month
Primary Wastes				
Grout Case 2 with LDR pretreatment (2g2)	1092 m3	8.4 m3	130	26
Grout with LDR pretreatment & 99% Sr-90 removed (2f)	1092 m3	8.4 m3	130	26
Steam Reforming Case 2 (3b)	727 m3	8.4 m3	87	8
Secondary Wastes				
Solidified Liquid Secondary Wastes from Vit (1c primary Vit to IDF & secondary to WCS)	12 m3	2.5 m3	5	1 every 3 months
Pretreatment Waste containing Tc-99 (from 2e2)	13 m3	2.5 m3	6	1 every 3 months

To summarize, Table G-4, the transportation of the Grout Case 2 WF, on average, will require a single train with 26 gondola railcars per month for the 28-year immobilization and disposal effort. Transportation of the Steam Reformed Case 2 WF, on average, will require a single train with 8 gondola railcars per month. A train every 3 months with 78 gondola rail cars (Grouting) or 24 gondola railcars (Steam Reforming) could improve efficiency (two extra sets of gondola railcars would need to be purchased for shipping every 3 months).

Routing

Figure G-5 presents the map of one possible rail route from Richland to WCS, travelling southeastward from Richland. The rout was chosen because it is more direct than going south through California, and the route shown goes through states with lower population densities. The rail route show in Figure G-5 was obtained with TRAGIS, the Oak Ridge National Laboratory routing tool assuming dedicated train. The route starts at Richland, WA railnode and ends at Eunice, NM railnode. WCS will send their locomotive the short distance to Eunice, NM to bring the railcars to their facilities in Texas. The total distance is 2232 mi. The calculated travel time by dedicated train is 79 hours (3.3 days).

The route requires the use of three rail companies: Burlington Northern Santa Fe, Union Pacific, and the Texas & New Mexico Railway. The information on the distance traveled is summarized below. There are three transfers along the route:

- From Union Pacific to Burlington Northern Santa Fe in Cheyenne, WY. Distance 1309 miles.
- From Burlington Northern Santa Fe to Union Pacific in Sweetwater, TX. Distance is 856 miles.

- From Union Pacific to Texas & New Mexico Railway in Monahans, TX. Distance 67 miles to Eunice, NM.

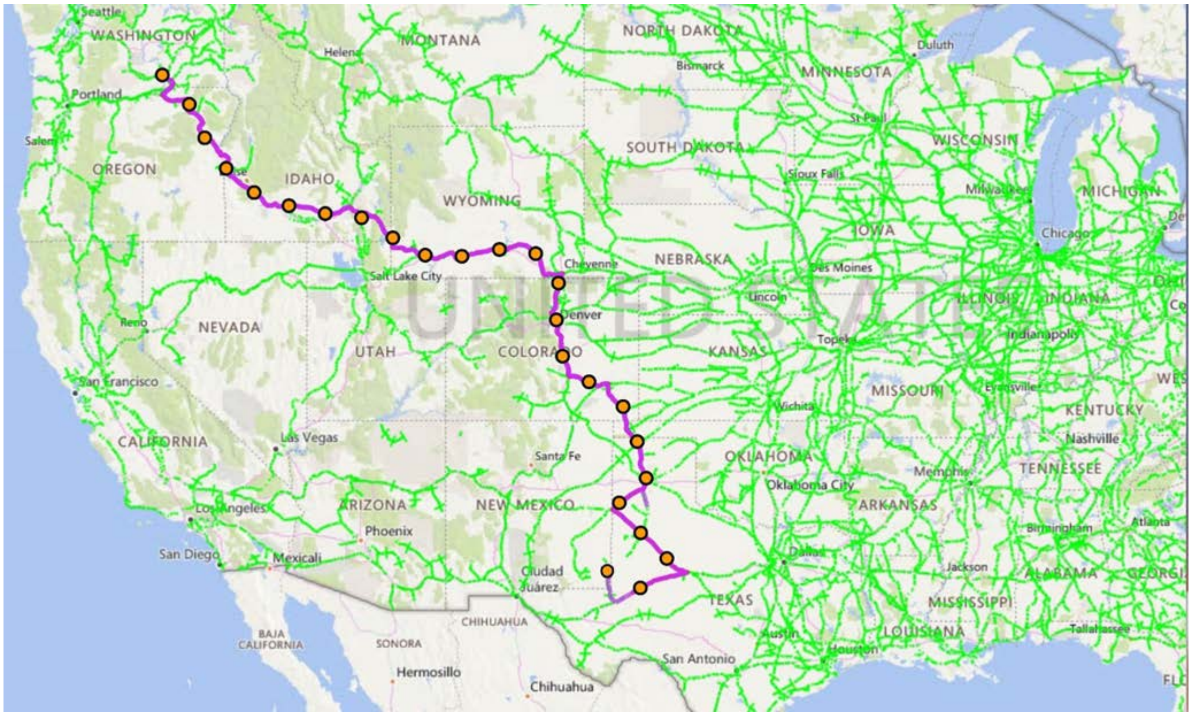

Figure G-5 Rail Routes and the Selected Dedicated Train Rail Route

G.9 COSTS

Rail shipping rates are confidential, and there are no "look-up tables" to assess the cost to ship immobilized SLAW by rail from Richland, Washington to WCS (i.e., Eunice, New Mexico). DOE's Office of Packaging and Transportation has placed several contracts to use rail to ship DOE radioactive wastes to disposal facilities, and based on their recommendation, this study will use $12,500 per loaded gondola for transport from Richland WA to Eunice NM, and $3,000 to bring the empty gondola railcars back to Richland.

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Table G-5 Railroad Cost to Ship Primary Wasteforms from Richland to WCS

Wasteform	**Average number railcars per month**	**Total Cost** for 337 months
Grout Case 2 with LDR pretreatment[113]	26	**$0.136 B**
Steam Reforming Case 2	8	**$0.042 B**

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[113] Removing the Sr-90 does not change the shipping cost, so Grout with LDR pretreatment & 99% Sr-90 removed (variant 2f) will cost the same to ship

G.10 TECHNICAL RISKS

G.10.1 Transportation Risks for Transport from Hanford to WCS

The transportation of goods by truck and railcar increases the amount of traffic, which increases the likelihood of traffic accidents and fatalities; in addition to increasing impacts to air quality, noise, and infrastructure. Statistically, these impacts are largely proportion to the number of miles traveled and independent of the cargo; transporting concrete blocks and transporting radioactive grout are the same.

Transporting radioactive materials brings additional risks, including potential doses to workers and the public from routine transport, and from transportation accidents.

The National Environmental Policy Act is a U.S. law that requires Federal agencies to prepare an assessment of potential environmental impacts; to accompany reports and recommendations for Congressional funding. Actual implementation of a shipping program, such as outlined here, would probably require the development of an Environmental Impact Statement (EIS) that would detail potential impacts to: air quality, ecological resources, historic and cultural resources, noise, public and occupational health, etc.

For the transport of radioactive materials, the EIS analysis of a large transportation program might specifically address:

- **Non-radiological Impacts on Local and National Traffic** -The impacts of additional trains on local and national tracks and the associated impacts to: air quality, noise, and infrastructure
- **Non-radiological Impacts of Transportation Accidents** - Statistical number accidents and fatalities from a proposed transportation program
- **Radiological Impacts of Routine Transportation** - Dose to a maximally exposed individual and the projected dose to the population along the route, and
- **Radiological Impacts of Transportation Accidents** - Statistical doses from a hypothetical accident.

This NDAA study is not scoped to provide the detailed analysis of potential transportation impacts that is sometimes provided in an EIS.

In particular, the assessment of radiological impacts will need to be specific to

1. dose rate on the outside of the shipping package(s)
2. the radiological content of the material(s) being shipped
3. the form of the waste (solid, powder, liquid)
4. the packaging
5. the quantities
6. 6) the mode (truck or rail)
7. possible accident scenarios for those wasteforms
8. the routing and population densities along the route.

For those interested, the West Valley Demonstration Project Waste Management Environmental Impact Statement (2003) (WVDP EIS) provides an example of an EIS for a major transportation program, including the shipping of LLW by rail to a disposal facility. The technical details of this EIS transportation analysis are presented in Appendix D of the DOE/EIS-0337F (available at https://www.energy.gov/sites/prod/files/EIS-0337-FEIS-Appendices-2003.pdf).

G.10.2 Non-radiological Transportation Risks for Hanford To WCS Scaled from West Valley

Many of the non-radiological transportation risks are proportional to the miles traveled, and some of the *relative,* non-radiological, risks can be assessed by scaling the analysis from an analogue EIS of the safety of the rail transport of other radioactive wastes. The WVDP EIS contains a non-radiological transportation risk assessment that can be scaled to provide a sense of the relative risks of this transportation program.

The closest analogy from the WVDP EIS to the proposed program to transport immobilized SLAW from Hanford to the commercial WCS disposal facility is based on the following in the WVDP EIS: Alternative A, rail transport of all LLW and MLLW from the WVDP to Hanford (Hanford was once considered as a regional disposal facility for DOE-title LLWs). Specifically, under Alternative A, DOE would ship Class A, B, and C LLW (19,200 m3) and mixed LLW (221 m3) to the DOE potential disposal site in Washington. Table G-6 summarizes key parameters for this NDAA study and those selected from the WVDP EIS.

Table G-6 Key parameters for the NDAA 3134 Study and Key parameters from WVDP EIS

Parameter	**This NDAA 3134 Study**	**WVDP EIS (DOE/EIS-0337F)**
Mode	Rail	Rail
Transportation distance (one-way)	2,200 miles (Hanford to WCS)	2,614 miles (WVDP to Hanford)
Type of Wastes	MLLW	LLW and MLLW
Number of railcars, Grout Case 2	312 (1 years of grout at 26 railcars per month)	615 (all LLW+ MLLW, Alternative A, Table G-3)
Number of railcars, Steam Reformed Case 2	96 (1 years of Steam Reformed at 8 railcars per month)	615 (all LLW+ MLLW, Alternative A, Table G-3)

Although not an exact match, the two transportation programs are very similar, with both programs assessing the impacts of the rail transport of LLW and MLLW over roughly 2,400 miles.

Transportation impacts from the WVDP EIS, for rail transport, for Alternative A, for all LLW and MLLW for the 2,614-mile trip are presented in Table D-16 of Appendix D of the WVDP EIS and summarized in column 2 of the Table below. Those column 2 values are then scaled to provide relative transportation risks for this NDAA study and presented in columns 3 through 6.

Because the WVDP EIS assess impacts per railcar mile, two translation factors were applied to scale the WVDP EIS analysis to this NDAA transportation scope; a scaling for the differences in the transportation distances and a scaling for the difference in the number of railcars. The translation factors are detailed as footnotes to entries in Table G-7.

Table G-7 Relative Nonradiological Risks, Scaled from WVDP EIS to this NDAA Study

Impacts	**Summed WVDP impacts**, for rail, for Alter. A, for all LLW+MLLW	One average year of impacts, for Hanford **Grou**t based on WVDP Impacts	**28 Years of impacts, for Hanford Grout scaled from WVDP Impacts**	one average year of impacts, for Hanford **SFGP** based on WVDP Impacts	**28 Years of impacts, for Hanford SRGP scaled from WVDP Impacts**
Traffic Fatalities	0.10	0.086^{A}	2.4	0.027^{B}	0.75
Incident-free, Pollution Heath Effects	0.024	0.021^{A}	0.58	0.0065^{B}	0.18

A - WVDP multiplied by 0.51 (312/615 correction for # of railcars) & multiplied by 1.68 (4400/2614 correction for distance traveled)
B - WVDP multiplied by 0.16 (96/615 correction for # of railcars) & multiplied by 1.68 (4400/2614 correction for distance travel)

For this NDAA study, the scaled statistical number of non-radiological rail traffic fatalities range from 0.75 to 2.4 for the summed 28 years of shipping immobilized SLAW.

The WVDP EIS transportation analysis is based on rail accident rates complied 20 years ago in 1999 (page D-11 of the WV EIS). To increase confidence in this scaled analysis, current DOT statistics for rail fatalities were reviewed. The *National Transportation Statistics 2018,* published by the DOT's Bureau of Transportation Statistics is available at https://www.bts.gov/browse-statistical-products-and-data/national-transportation-statistics/national-transportation-6. Table 2-39 of these national statistics presents the total number of train fatalities by year from railroad accidents (derailments, collisions) and accidents at highway-rail grade crossings. On average, there were <u>760 fatalities per year</u> based on a 11-year average (2006-2016, inclusive). "Trespassers" accounted for roughly one-half of those fatalities. Table 2-43 of the national statistics presents the number of Train-miles per year. A Train-mile is the movement of a train (which can consist of many cars) the distance of 1 mile. A Train-mile differs from a vehicle-mile, which is the movement of 1 vehicle the distance of 1 mile. On average, there were <u>741 million Train-miles per year</u> based on a 11-year average from 2006 through 2016 (inclusive).

Combining the statistics, there was an average of 1.0 fatalities per million Train-miles for the years 2006 through 2016. For a train from Richland to WCS, the roundtrip distance is 4,400 miles, and assuming one train per month, a total of 53,000 Train-miles per year, which (statistically) would result in 0.053 fatalities per year and statistically 1.48 fatalities over the full 28-year program. If the Grout Case 2 were shipped every 3 months (78 gondola railcars per train every 3 months, instead of 26 every month), <u>the statistical number of fatalities for the 28-year program would drop to 0.50 fatalities.</u> To put this impact (0.5 statistical fatalities in 28 years) in context, 28 years of baseline rail operations will result in 21,280 statistical fatalities (=28x760). Stated differently, one half of a statistical fatality is 0.002 percent increase in rail fatalities over the 28-year program.

G.11 PROGRAMMATIC RISKS

This NDAA 3134 Study completed a semi-quantitative assessment of risks, based on an elicitation of subject matter experts. This elicitation of risks identified:

- initiating scenarios that could give rise to deviations from design/operational intent
- the probability of the initiating scenario
- the unmitigated consequences
- the means of mitigating such events
- a probability of a successful mitigation, and
- the cost and schedule consequences of the mitigation.

This semi-quantitative assessment of risks identified and analyzed one Programmatic Risk for the offsite transportation program: Political opposition, in a major city on the rail route, following a rail accident, causes DOE to temporarily stop the shipping program.

Based on experience, the Probability of this occurring is: Low. However, the Unmitigated consequences were judged to be: Very high costs and Very high schedule impacts.

The Mitigation Strategy is to: change rail route or shift to shipping by truck. The Probability of Mitigation Success is: Very High and the Mitigation Consequences were assessed to be: Low cost and low schedule.

G.12 AREAS FOR FURTHER ANALYSIS

If additional funding was available, a detailed waste- and route-specific analysis of transportation impacts could be completed. This impacts study could address:

- Impacts on Local and National Traffic from Routine Transportation (air quality, noise, and wear-and-tear)
- Non-radiological Impacts of Transportation Accidents (statistical number accidents and fatalities)
- Radiological Impacts of Routine Transportation (dose to maximally exposed individual and dose to the population along the route)
- Radiological Impacts of Transportation Accidents (statistical doses from a hypothetical accident.

G.13 CONCLUSIONS

The key take-away from this detailed analysis is that the primary WFs (Grout Case 2 and Steam Reforming Case 2) and the secondary WFs can be safely transported from Richland to the WCS disposal facility in Texas. Both primary WFs meet the NRC's criteria to be shipped in packages meeting IP-II criteria as LSA material, the NRC's least hazardous category of material for shipping. The secondary WFs will need to be shipped in stronger Type A boxes, but no WF will require the rigorous Type B shipping cask.

Transportation of the Grout Case 2 WF, on average, will require a single train with 26 gondola railcars per month for the 28-year immobilization and disposal effort. Transportation of the Steam Reformed Case 2 WF, on average, will require a single train with 8 gondola railcars per month. A train every 3 month with 78 gondola rail cars (Grout) or 24 gondola railcars (Steam Reformed) could reduce the impacts of the shipping program. The technology readiness level is very high, as the DOE currently ships similar wastes for offsite disposal by rail.

APPENDIX H. COST ESTIMATE METHODOLOGY AND RESULTS

H.1 SUMMARY

This appendix presents capital and life-cycle cost estimate ranges for each Supplemental Low Activity Waste (SLAW) technology. These are provided as Class 5, Business Decision Estimate Ranges (BDER) based on the criteria found in the Association for the Advancement of Cost Engineering, International (AACEI), recommended practices.

H.2 ESTIMATE PURPOSE

The purpose of this appendix is to provide a Rough Order of Magnitude (ROM) Class 5 Planning Estimate for research and development, design, construction, life cycle costs including transportation and disposal. It also includes the disassembling and disposal cost for each technology; vitrification, grout and steam reforming, providing the most quantitative comparison possible between the base-case treatment options.

Class 5 estimates have the least project definition available (from 0% to 2%) and therefore have very wide ranges. They are the fastest of the five types of estimates to complete, but they are also the least accurate. These estimates were developed from information mined from previous studies, current Department of Energy (DOE) facility construction projects and current DOE operating facilities.

The Federally Funded Research and Development Center (FFRDC) team Subject Matter Experts (SME) identified technical and / or programmatic gaps between selected facility analogs and the pertinent technology. Adjustments were made to reflect the scale of these gaps – both in the total calculated cost and the confidence range of each estimate.

The accuracy associated with Class 5 estimates ranges from -20% / -50% to -30% / +100% and is a measure of the accuracy of the estimate after application of the Estimate Reserve. For this process, the accuracy reflected is -10% to +100% for the primary capital facilities.

Basic scope estimates for design, field installation and life cycle costs, including transportation and disposal will be developed by identification and utilization of analog facilities utilizing similar processes. The following assumptions have been made for the planning estimates provided.

H.3 ESTIMATE SCOPE

- Perform Technology Development activities.
- Procure Engineering / Design Subcontractor.
- Perform design, via subcontract, of facilities for SLAW including utility and process rooms, sample collection stations, office space, control room as applicable, lag storage feed tanks, lag storage for containers with appropriate containment, truck and or rail unloading / loading facilities.
- Provide design oversight of Engineering / Design Subcontractor for above.
- Procure Nuclear and Criticality Engineering Subcontractor services.
- Procure competitive bid for Construction Subcontractor.
- Construct SLAW Facilities as detailed above.
- Provide construction oversight of Construction Subcontractor.

- Subcontract (as appropriate) for offsite waste disposal including transportation.
- Maintenance and Operations of the Lag Storage Tank – common to all technologies.
- Secondary waste generation and disposal.
- Life cycle costs including transportation.
- Costs for electricity and other utilities.
- Operations & Maintenance training costs and Operations & Maintenance staff.
- Truck drivers, trucks and shipping costs.
- Decommissioning and Dismantling (D&D) of the SLAW Facilities at the end of the project.

H.4 ESTIMATE ASSUMPTIONS

- Construction will be mostly performed in non-rad and non-hazardous waste environment except for systems being tied into WTP operating systems as required.
- Assumes this facility will be constructed within the vicinity of WTP unless option flowsheet specifies other; utilities will be within 200' of new buildings /trailer location.
- Construction Subcontractor will have sufficient Hanford trained craft and supervision to perform work.
- Construction Subcontractor will perform ground surveys of installation areas prior to work performed in accordance with construction schedule dates.
- Construction Subcontractor will perform ground surveys for soil disturbing activities in accordance with construction schedule dates.
- Lock and Tag-out and connecting to existing utilities will be performed by the Construction Subcontractor with Hanford Operations support.
- Construction Subcontractor will be responsible for disposal of construction waste.
- No existing utilities will have to be rerouted.
- Current existing utilities at new building locations are sufficient for capacity for supporting scope.
- Sufficient competition between Construction Subcontractors will be available ensuring a reasonable bidding and a project cost atmosphere.
- Replacement costs of installed engineered equipment during operations will be determined. This excludes consumable system units, such as melters or other key systems with known life expectancy.

H.5 ESTIMATE EXCLUSIONS

Assumes non-consumable installed equipment will last the life time of the project.

Estimate Flowsheets

Flowsheets were developed for the following options and sub options and support the development of the planning estimate, based on ORP-11242, revision 8, River Protection Project System Plan, as a general baseline.

An iterative process involving technology and regulatory SME input, development and construction experience, and operations and logistics expertise was used and the following analog facilities were identified for use in the process of estimating.

H.5.1 Vitrification

Waste Treatment and Immobilization Plant (WTP) – Low Activity Waste (LAW) with Effluent Management Facility (EMF) at the Hanford Site

Defense Waste Processing Facility (DWPF) at the Savannah River Site (SRS).

WTP-LAW was selected as the best analog for SLAW vitrification. The prescribed flowsheet uses the same melters (4 versus 2) and the pertinent seismic and nuclear construction requirements will be more current than for DWPF.

H.5.2 Grout

Saltstone, with defined upgrades and logistics beyond the scope of SRS operations.

Saltstone can produce at the same scale as required for SLAW grout. It is a good analog for scale, but significant pretreatment, handling (casting into 8.4m3 containers versus SDU's), and transportation logistics must be included.

H.5.3 Fluidized Bed Steam Reforming (FBSR)

Integrated Waste Treatment Unit (IWTU) at the Idaho Site.

IWTU is nominally half the capacity required for SLAW fluidized bed steam reforming, and will produce a different mineral (sodium carbonate versus aluminosilicate) form, and is built for more highly radioactive material. It is the best available analog, though not as similar relative to the grout or glass analogs.

H.6 ESTIMATE PLANNING

The planning estimates for the proposed SLAW projects were developed from information mined from previous studies, current DOE facility construction projects and current DOE operating facilities. Key in development was the use of direct comparison for specific ancillary facilities, namely:

- Pre-processing Facility
- New unit operations
- Post processing Facility
- Balance of Facilities
- Control Room

This approach relies on existing information such as actual construction costs (with escalation) for operating facilities (such as Saltstone) or facilities undergoing start-up (such as the IWTU) or Estimate at Completion (EAC) data for facilities nearing start-up (such as WPT-LAW). These data were then adjusted for the scale of the proposed facility versus the analog.

Vitrification and steam reforming options require double capacity of the closest analog. A multiplier, square root of 2, to capital costs of the analog was applied to reflect the increased footprint and the capacity required.

Cost estimating was also performed for selected variants for each case base. These variants, which were selected during the team evaluation exercise, were estimated in the same manner as the base cases. To reflect the degree of uncertainty for the estimating process, variants that did not appear to change the capital costs or operating costs on the order of at least 25% were usually not estimated to the same rigor, or at all.

The selected analog facilities provide the best available data for estimate bases. It is noted there is more deviation between certain analogs and the projected SLAW process. Adjustments were made to reflect significant increases in unit operations or complexity, or reductions in same. The intent of the exercise was to compare the range defined within a technology, identify the degree to which technology cost estimated ranges do or do not overlap, and so therefore provide a ROM comparison.

The FFRDC team identified technical and / or programmatic gaps between selected facility analog and the pertinent technology. Adjustments were made to reflect the scale of these gaps – both in the total calculated cost and the confidence range of each estimate.

Logistics and transportation were considerations identified for all options. Key facets of this portion of the estimate includes preparation and storage offsite shipment, transportation (nominally rail), and facility disposition (tipping fee). The study focused on only one offsite option, Waste Control Specialists, (WCS). WCS applies a volumetric charge to all incoming waste, within a given category.

Operating costs were estimated in a similar manner as capital costs. Analog facility costs, or estimates, were applied to the respective technologies. Allowances were made for additional tankage and unit operations, control room, laboratory and logistic support. As per capital outlay, vitrification and steam reforming operating costs were increased by a factor of the square root of 2, to account for the increased (double) number of systems versus the closest existing analog.

Scope requirements defined by the SMEs, as well as challenges and opportunities associated with the proposed process are as follows.

Vitrification: For the vitrification process, the following facilities are included.

1. Lag storage capability of 500K gallons (*consistent for all options*)
2. WTP SLAW Vitrification Facility with 4 melters and offgas systems
3. WTP Effluent Management with equivalent capability
4. Balance of Facilities, consistent with WTP LAW
5. Lag Storage and Shipping Capability, consistent with WTP LAW

It was assumed that the existing control room and laboratory could be utilized for this option with minimal impact to normal operations.

Another option for this process would be the use of two (2) larger melters and offgas systems. For transportation, an opportunity exists to use a rail system for glass container movement to the final storage location.

Grout: For the grout process, the following facilities are included.

1. Lag storage capability of 500K gallons
2. WTP LAW grout facility including pre-treatment tank (not specified) batch mixer, feed silos, hoppers, containerization and decontamination facility
3. Balance of Facilities, as required
4. Lag Storage and Shipping Facility

A new control room and expected use of the WTP laboratory with some shift adjustments are assumed for this process.

Scope for this process assumes the need to perform a generic pre-treatment unit operation, subsequently specified as organic treatment for LDR. Technetium (Tc) and/or Iodine (I) removal were also discussed by subject matter experts.

Another variant considered was construction of the grout plant at IDF – assuming large storage vaults would be employed.

Opportunities with type of shipping packaging and shipping options to final storage locations exist.

Steam Reforming: For the Fluid Bed Steam Reforming (FBSR) process, the following facilities are included.
1. Facility with two (2) IWTU Facilities lines utilizing the Denitration Mineralization Reformer (DMR) process
2. Lag Storage capability of 500,000 gallons
3. Installation of cryogenic nitrogen and oxygen tanks
4. Balance of Facilities, as required
5. Lag Storage and Shipping Facility (for off-site)

A new control room and expected use of the WTP laboratory with some shift adjustments are assumed for this process.

High scope for this process assumes a grout plant is required for each DMR unit to form a monolithic product.

H.7 WORK BREAKDOWN STRUCTURE

Typically, a WBS would have a minimum of 10 to 12 legs to identify specific line items for labor hours, dollars, engineered equipment, bulk material and such. For the approach taken for this evaluation, a bottoms up approach to develop the estimates was not used. The estimates represent the enhancement of technology development, Total Estimated Cost (TEC), the Other Project Costs (OPC), Operations/ Life Cycle costs, including transportation and Deactivation and Decommissioning costs.

Simplified WBS Elements are as follows:
- 01 Review and Enhancements of Technology Development
- 02 Engineering, Construction and Startup
- 03 Operations; annual operations and transportation costs
- 04 Deactivation and Decommissioning

No design has been completed for this process and the estimates are based on flowsheets developed for each set of technology base cases.

Estimate Reserve, Technical & Programmatic Risk Assessment and Schedule Contingency will be applied to the estimate at 50% for the low scope. For the high scope, 60% reserve was used.

H.8 PROJECT SCHEDULE

Project schedule assumes results of the Analysis of Alternatives (AoA) and a Project Requirements Document (PRD) will be completed in a timely fashion to support completion of technology development, design, construction and startup activities to support a startup of SLAW to support

WTP operations schedule.

Life cycle will run concurrent with WTP processing per System Plan 8.

- Commissioning beginning 2033
- Full operations in 2036
- HLW/LAW operations complete 2063

Decommission and Deactivation will proceed when authorized. Duration will be dependent on final state of the facilities impacted.

H. 9 PRIMARY COST DIFFERENCES AND FACTORS

The Life Cycle Cost (LCC) estimates for the three technologies show considerable variation. Vitrification has the highest projected cost range, FBSR is second, with grouting calculated to be the lowest cost option. There are 4 main portions of the individual cost estimates that determine the final LCC rankings:

1. Technology Development (TD) and Pilot Operations
2. Total Project Cost (effectively the capital project for SLAW)
3. OPEX Operating/Life Cycle Cost
4. Shipment to / Disposal at WCS.

1. **Technology Development and Pilot Operations** are significantly higher for vitrification and FBSR due to the nature of the testing (vitrification) and degree of maturity relative to the waste stream and application (FBSR). Technology development and testing for vitrification will be predominately focused on product rate and integrated operations. All primary HLW and LAW treatment will be vitrification based, resulting the largest total volume of primary plus secondary liquid waste to be processed through WTP-PT. Integrated testing to verify rate attainment will require significant system capability so as to provide necessary operational data, including extended duration testing for total system reliability. SLAW is reliant on WTP-PT and WTP-HLW, thus integrated testing will be a significant investment.

   FBSR is the least mature of the technologies regarding caustic liquid feed processing. The closest operational analog (IWTU) is designed to produce a lower temperature mineral form from acidic feed. The materials of construction capability and the throughput requirements are common parameters leading to integrated system testing and significant development and pilot efforts.

   Grouting has been demonstrated at scale for inherently similar caustic waste. However, the operational requirement to meet LDR must be developed and the associated unit operation(s) demonstrated. This effort will be the major facet of the TD necessary to fully evolve grout to a capital project.

2. **Total Project Cost** estimates reflect current WTP capital costs captured (WTP-LAW, Balance of Facility, and DFLAW) as applied to SLAW vitrification. It is recognized that these costs appear significantly greater than projected in the EIS; they are more in line with the recent GAO and DOE Life-Cycle Cost reporting, which also appear to rely on the updated WTP project costs. The project TPC cost for SLAW vitrification is considerable. It is noted that the SP 8 projected completion of the SLAW complex will mandate no fewer than 6 years wherein SLAW and WTP-PT plus WTP-HLW each require the current WTP line item (assumed here at $750M per year) for completion. This funding scenario is not consistent with the demonstrated path for the current WTP complex.

3. TPC of the FBSR and grout facility are derived from the closest analogs and scaled to match capacity (IWTU for FBSR) or cost escalated (SRS Saltstone for grout) to 2018. Grout is also amended to provide for significantly enhanced handling and logistics to include the LDR treatment – aspects not incorporated at Saltstone. It is noted these upgrades significantly increase the TPC for each technology versus the analog. At the same time, the projected costs are nominally consistent with other recent estimates and do not appear to force a doubling (as per vitrification) of capital outlay in conjunction with WTP-PT and WTP-HLW completion.

4. **OPEX Operating/Life-Cycle** cost estimating is based on the current project estimate for DFLAW (vitrification), IWTU start-up operational costs (FBSR), and Saltstone (grout). Grout OPEX costs are significantly increased to provide for the LDR treatment unit operation(s) and handling/logistics issues. Still these are significantly lower than FBSR, which is also less than DFLAW operation estimates (even accounting for removal of LAWPS, etc.). It is noted that this the largest gap between technologies and no overlap exists between associated cost ranges. Thermal processing is consistently shown to be higher in operating costs in the DOE complex and for international operations.

5. **Shipment to / Disposal at WCS** is a significant estimated cost for FBSR and the single highest cost source identified for grout. This cost is inherent to offsite disposition and so is not appropriate for vitrification – at least regarding primary wasteform disposition. Offsite disposition for grout equates to the range of 30-60 percent of the vitrification capital (TPC) outlay but would be paid systematically over the course of the multi-decade program.

Preliminary Summation of Base Scope Cost Numbers
Base and Variant Scopes Combined

Work Breakdown Structure, Basis and Cost Breakdown for Vitrification Technology

Base Case Scope
Waste concentrate feed tank with a capacity of 500,000 gallons
Design of the Vitrification facilities and support systems for the following key systems
Melter feed system capable of receipt and handling of treated waste
Melter feed preparation tanks (2)
Meter feed vessels (4)
Glass forming Chemical handling and blending system
Glass Forming Chemical Silos (13)
Glass Forming Chemical Hoppers (2)
Four (4) joule-heated, ceramic lined melters
Four (4) off-gas trains (primary and secondary systems)
Effluent Management Facility (EFM) and support systems
Effluent Treatment Facility (ETF) and support systems
Glass container handling & decontamination facility and support systems; existing canisters to be used
Temporary lag storage facility, support systems with truck loading capability
Expansion of existing Integrated Disposal Facility (IDF)

Work Breakdown Structure, Basis and Cost Breakdown for Vitrification Technology (continued)
Base Case

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	OPEX/Life Cycle Cost	Shipment to WCS	Major Equipment Replacement	Total Program Cost
$340M – $760M	$1,080M – $2,520M	$6,840M – $15,200M	$10,080M – $15,120M	N/A	$1400M – $2100M	$19700M – $35,700M

Estimate Basis
Estimate range is -10% to +100% for TPC, assuming FY18 costs and overheads, with no escalation applied for Technology Development, or Pilot Plant

Technology development is driven by current rate of R&D expenditure and expected lessons learned from WTP-LAW – set at 5% of TPC.
Pilot Plant costs includes design, construction and life cycle costs to maintain in place for life of the program
Total Project Costs (TPC) includes Total Estimated Costs (TEC), Other Project Costs (OPC), Contractor Support and all Facility Support to complete the design, build, test and startup of the facilities based on WPT-LAW with Effluent Management and Effluent Treatment Facility capability
OPEX/Life Cycle Costs includes routine operations, maintenance, engineering costs for running the facility over a span of 28 years at $450M per year (-20% / +20%).
Major Equipment Replacement driven by number of melter replacements (24) with associated bubbler sets.
Decommissioning & Demolition costs are beyond scope of this exercise.

Work Breakdown Structure, Basis and Cost Breakdown for Grout Technology

Base Case Scope

Waste concentrate feed tank(s) with a capacity of 500,000 gallons
Grout processing plant and support systems for the following key systems
Grout feed system capable of receipt and handling of treated waste
Dry mix silos, blending tank and feed hoppers
Batch mixer and container filling and decontamination station; designed for use of B25 containers
Temporary lag storage facility, support systems with truck loading capability
Expansion of existing Integrated Disposal Facility (IDF)

Variant Case Scope – Grout Pre-Treatment

Waste concentrate feed tank(s) with a capacity of 500,000 gallons
Grout processing plant and support systems for the following key systems
Grout feed system capable of receipt and handling of treated waste
Dry mix silos, blending tank and feed hoppers
Batch mixer and container filling and decontamination station; designed for use of B25 containers
Pretreatment facility to remove organics and metals to comply with Land Disposal Restrictions (LDR) with support systems
Tanks, pumps, resin beds, filters, etc.
Temporary lag storage facility, support systems, with truck loading capability
Expansion of existing Integrated Disposal Facility (IDF)
Product with Strontium (Sr) to be transported to Waste Control Specialist (WCS)

Work Breakdown Structure, Basis and Cost Breakdown for Cast Stone Technology (continued)

Base Case

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	OPEX/Life Cycle Cost	Shipment to WCS	Major Equipment Replacement	Total Program Cost
$90M – $210M	N/A	$500M – $1,120M	$1,120M – $1,680M	N/A	$130M – $280M	$1850M – $3280M

Variant Case – Offsite Grout with Pre-Treatment

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	OPEX/Life Cycle Cost	Shipment to WCS	Major Equipment Replacement	Total Program Cost
$120M – $260M	N/A	$650M – $1,440M	$1,120M – $1,680M	$2,780M – $4,160M	$160M – $360M	$4820M – $7900M

Work Breakdown Structure, Basis and Cost Breakdown for Cast Stone Technology (continued)

Estimate Basis

Estimate range is -10% to +100% for TPC, assuming FY18 costs and overheads, with no escalation applied for Technology Development.

Technology development lower (absolute versus relative) because of non-thermal testing and existing maturity

Pilot Plant not required; simple, proven technology

Total Project Costs (TPC) includes Total Estimated Costs (TEC), Other Project Costs (OPC), Contractor Support and all Facility Support to complete the design, build, test and startup of the facilities based on Saltstone

IDF expansion costs are for design and construction of new facility within boundaries of existing permits

OPEX/Life Cycle Costs includes routine operations, maintenance, engineering costs for running the facility over a period of 28 years at $40M per year with a +50% estimate range

Shipments of material to Waste Control Specialist (WCS) is assumed to be by rails and includes cost of rail service and WCS fee for receipt; 397,000 m^3 equaling 716,300 tons of material at $0.06 cents per mile (includes return of cars) for 2,200 miles, one way and WCS cost of $7K per m^3 with a +50% estimate range

Major Equipment Replacement addresses major components that will be replaced during the life cycle of the program and has a -30% to +50% estimate range

Work Breakdown Structure, Basis and Cost Breakdown for Fluid Bed Steam Reforming Technology

Base Case Scope
Waste concentrate feed tank with a capacity of 500,000 gallons
Waste feed tanks, two (2) at 50,000 gallons each
Waste mix/feed tanks, two (2) at 30,000 gallons
Design of two (2) new Fluid Bed Steam Reforming (FBSR) facilities and support systems for the following key systems
FBSR feed system capable of receipt and handling of treated waste
Clay additive system
Denitration mineralizing reformer and process gas filter
Off-gas control system with thermal oxidizer, carbon absorber, wet scrubber, re-heater and HEPA filters
Gas supply systems; oxygen, nitrogen, etc.
Product handling & decontamination facility and support systems
Geopolymer monolith system with support systems for clay addition, chemical and water addition and waste container handling capabilities
Temporary lag storage facility, support systems, and truck and or rail loading capability
Expansion of existing Integrated Disposal Facility (IDF)

Variant Case Scope – Granular Product to WCS
Waste concentrate feed tank(s) with a capacity of 1,000,000 gallons
Waste feed and mixing tanks, two (2) at 250,000 gallons
Design of two (2) new Fluid Bed Steam Reforming (FBSR) facilities and support systems for the following key systems
FBSR feed system capable of receipt and handling of treated waste
Clay additive system
Denitration mineralizing reform and process gas filter
Off-gas control system with thermal oxidizer, carbon absorber, wet scrubber, re-heater and HEPA filters
Gas supply systems; oxygen, nitrogen, etc.
Product handling & decontamination facility and support systems
8.4 cubic meter disposal bag inside an 8.4 cubic meter reusable transport box
Temporary lag storage facility, support systems with railcar loading capability
Product transported to Waste Control Specialist (WCS)

Work Breakdown Structure, Basis and Cost Breakdown for Fluid Bed Steam Reforming Technology (continued)

Base Case

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	OPEX/Life Cycle Cost	Shipment to WCS	Major Equipment Replacement	Total Program Cost
$480M – $1,080M	$1,080M – $2,520M	$1,930M – $4,300M	$2,520M – $3,780M	N/A	$290M – $650M	$6300M – $12,3300M

Variant Case – Granular Product to WCS

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	OPEX/Life Cycle Cost	Shipment to WCS	Major Equipment Replacement	Total Program Cost
$480M – $1,080M	$1,000M – $2,600M	$2,310M – $5,140M	$3,270M – $4,900M	$1,850M – $2,780M	$330M – $740M	$9240M – $17,240M

Estimate Basis

Estimate range is -10% to +100%, for TPC, with no escalation applied for Technology Development, or Pilot Plant.
Technology development is driven by greater uncertainty on product formulation versus vitrification and testing expense.
Pilot Plant costs includes design, construction and life cycle costs to maintain in place for life of the program
Total Project Costs (TPC) includes Total Estimated Costs (TEC), Other Project Costs (OPC), Contractor Support and all Facility Support to complete the design, build, test and startup of the facilities based on IWTU facility
IDF expansion costs are for design and construction of new facility within boundaries of existing permits
OPEX/Life Cycle Costs includes routine operations, maintenance, engineering costs for running the facility over a period of 28 years at $146M per year for base case and $112M per year for variant case with a -20% / +20% range.
Shipments of material to Waste Control Specialist (WCS) is assumed to be by rails and includes cost of rail service and WCS fee for receipt; 245,300 m^3 equaling 216,000 tons of material at $0.06 cents per mile (includes return of cars) for 2,200 miles, one way and WCS cost of $7K per m^3 with a +50% estimate range
Major Equipment Replacement addresses major components that will be replaced during the life cycle of the program and is estimated at 15% TPC.

Decommissioning & Demolition costs reflected are assumed to be the same as Vitrification Technology for comparison purposes.

H.10 COST ESTIMATES COMPARED WITH EARLIER EFFORTS

Cost estimating for the WTP complex and related SLAW complex reflects significant increases across the span of the WTP construction effort. WTP cost estimate increases are documented and reflect status at various completion percentages. SLAW to date has never been projectized. Uniformly, cost estimates for SLAW vitrification have tracked some percentage of the WTP LAW or DFLAW efforts. Cost estimates for technologies other than vitrification have been based on analogs and/or parametric studies at the ROM level.

Information available to inform the Hanford Environmental Impact Statement (EIS)[114] consistently provided WTP LAW Forecast at Completion costs ≤ \$1.7B. A current (2017) status per the GAO provides a nominal WTP-LAW completion estimate at \$6.5B - potentially higher (some value less than \$8.3B), depending on how DFLAW costs are apportioned, clearly demonstrating the project challenges and cost escalation. This updated information was incorporated into this work to evaluate a SLAW vitrification project cost and consider how a SLAW project would fit alongside completion of WTP-PT and WTP-HLW. For reference, WTP-PT and WTP-HLW were reflected as 2.6X and 1.7X more expensive than WTP-LAW, respectively in the same source documentation.[115]

SLAW, as considered here, is twice the scale (as capacity) for WTP-LAW and includes internal recycle plus all necessary Balance of Facility (BOF) services. The conceptual flowsheet is almost identical to DFLAW; the number of unit melter process lines is only 1 greater than initially designed for WTP-LAW. Information timely for the EIS and later used in System Plan 6 has a SLAW facility cost of ≈ \$1B, considerably lower than provided for the smaller WTP-LAW facility (which shared BOF costs with WTP-PT and WTP-HLW). The range provided here reflects the lower end of WTP-LAW realized costs and a higher end reflecting the additional BOF, recycle capability, and projected start-up plus the uncertainty of completing 3 major capital projects within 1 year with associated funding competition. SLAW FBSR or grout options facilities, by necessity for this study, be constructed alongside WTP-PT and WTP-HLW. As such, similar uncertainty was provided in the estimate range.

OPEX/Life Cycle costs for SLAW vitrification reflect a similar increase versus information guiding the EIS. The working projected cost for DFLAW is on the order of \$400M annually, whereas total WTP-LAW commissioning cost projected in advance of the EIS was on the order of \$180M. For reference, System Plan 8 has an estimated cost for SLAW vitrification (again a larger facility than WTP-LAW) of \$340M. The estimate projected herein ranges close to System Plan 8 (low end) but also reflects operations of a 2X facility plus associated BOF.

One other principal deviation between the cost estimates for grout and FBSR off-site options and the EIS values is that WCS was not a suitable, licensed facility during preparation of the EIS. The estimates projected rang from nominally \$1.3B, reflecting current pricing and transportation (low end) to nominally \$4B reflecting project uncertainty for ROM estimating. This is balanced by the methods for encapsulating the wasteforms reflected in the EIS (more akin to vitrification) versus current commercial radwaste transportation and disposal methods.

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[114] "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington." DOE/EIS-0391. November 2012. U.S. Department of Energy.

[115] Bechtel National, Inc. Summary of May 2006 EAC to-Go Costs by Facility, as found in RPP-RPT-47908, Rev. A.

APPENDIX I. REGULATORY COMPLIANCE

I.1 REGULATORY BACKGROUND

The portion of low-activity waste at the Hanford Nuclear Reservation, Richland, Washington, that is intended for supplemental treatment and addressed in this assessment is managed through U.S. Department of Energy's (DOE's) radioactive waste management activities as prescribed under various DOE orders, including DOE Order 435.1 (DOE O 435.1), "Radioactive Waste Management".[116] DOE O 435.1 was promulgated under Atomic Energy Act of 1954, as amended. DOE is the responsible party for the safe management and final disposal of all radioactive wastes arising from its operations. The objective of the activities required under this order is to ensure that the waste is managed in a manner that is protective of worker and public health and safety, and the environment.

DOE O 435.1 requires that radioactive waste at DOE sites be managed to comply with applicable Federal, State, and local laws and regulations as well as Executive Orders and other DOE directives. Based on the guidance provided in DOE M 435.1-1, the regulations that may be applicable to the Hanford Site for the supplemental treatment of low activity waste, at a minimum, include:

- Resource Conservation and Recovery Act (RCRA) requirements (40 CFR Parts 260—273) for mixed low-level waste[117] (See Ref. 1);
- Applicable sections of Washington State (WA) regulations (WAC 173-303) that implement RCRA requirements (See Ref. 2);
- Clean Air Act (CAA) implementing regulations at 40 CFR Subchapter, Parts 50-97 (See Ref. 3);
- Applicable sections of WA air regulations to include, criteria pollutants (WAC 173-400), toxic air pollutants (TAPs) (WAC 173-460), and radioactive air pollutants (WAC 246-247) (See Ref. 4 to 6);
- Occupational Radiation Protection requirements (10 CFR Part 835) for oversight of radioactive waste management facilities, operations, and activities;
- Toxic Substances Control Act (TSCA) requirements (40 CFR Part 761) for low-level waste containing polychlorinated biphenyls, asbestos, or other such regulated toxic components[118] (See Ref. 7); and
- As low as reasonably achievable (ALARA) exposure requirements under Radiation Protection of the Public and the Environment (10 CFR Part 834) and DOE 5400.5

In addition to the regulations listed above, various transportation and packaging requirements are applicable for onsite or offsite waste disposal. Packaging and transportation requirements are discussed in Chapter 7 in more detail. However, some applicable regulations include DOE orders 435.1, 460.1A, and 460.2, and other Department of Transportation (DOT) requirements.

This chapter focuses on the regulations that are applicable to management and disposal of the portion of low-activity waste at the Hanford Nuclear Reservation intended for supplemental treatment. It summarizes an analysis of the compliance of treatment approaches with applicable technical standards associated with and

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[116] DOE Order 435.1 governs the management of radioactive waste at DOE sites, including criteria for wastes that are not considered high-level.

[117] Under DOE M 435.1-1 Section IV.B.(1), ***Mixed Low-Level Waste*** is the low-level waste determined to contain both source, special nuclear, or byproduct material subject to the Atomic Energy Act of 1954, as amended, and a hazardous component subject to the Resource Conservation and Recovery Act (RCRA), as amended, and shall be managed in accordance with the requirements of RCRA and DOE O 435.1.

[118] Under DOE G 435.1-1 Section IV.B, ***TSCA-Regulated Waste*** is the low-level waste containing polychlorinated biphenyls, asbestos, or other such regulated toxic components, and shall be managed in accordance with requirements derived from the Toxic Substances Control Act, as amended, and DOE O 435.1.

contained in regulations prescribed pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (42 U.S.C. 9601 et seq.), the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.), the Federal Pollution Control Act (33 U.S.C. 1251 et seq.), the Clean Air Act (42 U.S.C. 7401 et seq.), and any corresponding State law.

I.2 DESIGNATION OF HANFORD WASTE

In 1997, DOE and Nuclear Regulatory Commission (NRC) provisionally agreed that the vast majority of waste from Hanford tanks is not high-level waste, but rather is low-level waste that is not subject to NRC's licensing authority.[119] The Hanford waste slated for disposal as low activity waste must be determined to meet the Waste Incidental to Reprocessing (WIR) criteria in DOE M 435.1-1(See Ref. 8). Incidental waste is managed under DOE's regulatory authority in accordance with the requirements for low-level waste, as appropriate.

Hanford incidental waste to be managed as low-level waste must be documented to meet the following criteria:

1. Have been processed, or will be processed, to remove key radionuclides to the maximum extent that is technically and economically practical;
2. Managed to meet the safety requirements comparable to the performance objectives set out in 10 CFR Part 61, Subpart C, Performance Objectives; and
3. Managed pursuant to DOE's authority under the Atomic Energy Act of 1954, as amended, and in accordance with the provisions included in DOE M 435.1-1, Chapter IV, provided the waste will be incorporated in a solid physical form at a concentration that does not exceed the applicable concentration limits for Class C low-level waste as set out in 10 CFR 61.55, Waste Classification, or will meet alternative requirements for waste classification and characterization as DOE may authorize.

If the waste stream is shown to meet the criteria above, then it can be disposed in a near-surface permitted facility. For Hanford's tank waste, criterion 1 is addressed through pretreatment processing of the tank waste either through the pretreatment facility within the WTP or the Low Activity Waste Pretreatment System (LAWPS) as shown in Fig. 2-1. This pretreatment processing, principally for removal of Cs and undissolved solids removes key radionuclides necessary to meet criterion 1. For this assessment, the LAW feed vector represents a post-pretreatment feed stream that has been processed to addressed criterion 1. Criterion 3 is addressed principally through the LAW processing to ultimately produce a LAW wasteform, either through WTP LAW vitrification, or through SLAW immobilization and any additional pretreatment options considered. Therefore, this assessment must address criterion 3 by selection and evaluation of processing options that will meet the solid physical form and concentration requirements of this criterion. Finally, criterion 2 is addressed through both the wasteform and the disposal site considerations. Disposal sites demonstrate compliance with criteria 2 by developing performance assessment analyses, considering both the inventory of radionuclides, wasteforms, and disposal site specific designs and environmental conditions to assess long-term compliance with prescribed performance objectives that meet or exceed the requirements of 10 CFR Part 61, Subpart C, Performance Objectives. This assessment must address this criterion, to the extent practical and appropriate given the wasteform performance data and analysis available.

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[119] Kinzer, J. (Jun 23, 1997). *Contract Number DE-AC06-96RL13200 – Nuclear Regulatory Commission (NRC) Agreement on Classification of Hanford Tank Waste* [Memorandum]. Washington, DC: Department of Energy.

I.3 HANFORD WASTE CLASSIFICATION UNDER RCRA AND TSCA

The Hanford tank waste is considered "mixed waste"—hazardous waste mixed with radioactive material. Therefore, in addition to DOE orders, it is regulated under the Environmental Protection Agency's (EPA) Resource Conservation and Recovery Act (RCRA) that governs the treatment and disposal of solid and hazardous waste. EPA has delegated its RCRA authorities to Washington State, who implements these requirements under WAC 173-303, *Dangerous Waste Regulations*.

Hanford is considered a single facility for purposes of RCRA and the Washington State Hazardous Waste Management Act. The permit is referred to as the *Hanford Site-Wide Permit Revision 8C* (See Ref. 9), and the site has been issued EPA/state identification No. WA7890008967. The permit sets conditions based on the state's laws and regulations that control the treatment, storage, and disposal of dangerous wastes The single shell tanks (SSTs) and double shell tanks (DSTs) are identified as individual units in the Permit. The DST farms operate under interim status requirements. A Part B permit application for the DSTs was submitted to Ecology in 2005. The TPA lays out the process and authority to operate non-RCRA-compliant SSTs pending closure and identifies the process and procedures for SST system closure.

The RCRA Program establishes two ways of identifying solid wastes as hazardous: (1) a waste is considered hazardous if it exhibits certain hazardous "characteristics" (i.e., ignitability, corrosivity, reactivity, or toxicity); or (2) a waste is considered hazardous if it is "listed" in EPA's list of hazardous wastes. Based on these characteristics and listed wastes, specific waste codes that have been assigned to Hanford tank waste are given in Table I-1 for the characteristic hazardous wastes, Table I-2 for listed hazardous wastes, and Table I-3 for WA State-only waste classifications, below.[120] These codes are identified in the RCRA Part A issued by Ecology for both the SSTs and the DSTs. The waste codes were determined either by chemical analyses of the tank waste, or by process knowledge, as provided in WAC 173-303.

A new supplemental treatment unit would likely require a final status RCRA permit to be issued by Ecology. The RCRA regulations require a completed, certified engineering design. In the past, Ecology has worked with the DOE to allow the permitting process to begin as the design is being finalized. The Toxic Substances Control Act (Toxic Substances Control Act of 1976 (15 U.S.C. 2601 et seq.) provides EPA with the authority to require testing of chemical substances entering the environment and to regulate them as necessary. (See Ref. 9) Under TSCA, EPA is also authorized to impose strict limitations on the use and disposal of polychlorinated biphenyls (PCBs). The EPA regulations that establish prohibitions of, and requirements for PCBs and PCB items are found in 40 CFR 761, "*Polychlorinated Biphenyls (PCBs) Manufacturing, Processing, Distribution in Commerce, and Use Prohibitions*".

In August, 2000, the EPA, DOE and Ecology entered into the "The Hanford PCB Framework Agreement," that provided their approach to resolve the regulatory issues with managing PCB remediation waste at the vitrification plant, tank farms (to include tank waste retrievals, transfers, and contaminated equipment), and affected upstream/downstream facilities to further the timely treatment and disposal of tank waste. (See Ref. 10) They further agreed that they would pursue a rational path based on a risk-based disposal approval option per 40 CFR 761.61 (c) for management of TSCA PCB remediation waste.

The parties also agreed that RCRA and the CAA, as implemented through approved State programs, and Atomic Energy Act are expected to be the key regulatory drivers for tank waste retrieval, transfers, pretreatment, vitrification, disposal, and other activities impacted by the designation of tank waste as PCB remediation waste.

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[120] RPP-8402, Rev.1., DRAFT, Integrated Disposal Facility Waste Acceptance Criteria, 2005.

The engineering design basis for the vitrification plant assumes up to 50 parts per million of PCBs in the waste feed to the vitrification plant.

DOE has submitted two risk-based disposal applications to EPA Region 10 for their approval. The first application, titled “Transmittal of Toxic Substance Control Act (TSCA) Risk-Based Disposal Application for the Double Shell Tank (DST) System for 2001,” was submitted on January 2002. (See Ref. 11) The second application, titled “Application for Risk-Based Disposal Approval for PCBs Hanford 200 Area Liquid Waste Processing Facilities,” was submitted on February 28, 2002. (See Ref. 12)

An EPA risk-based disposal approval will be required for a new supplemental treatment plant. Past experience at Hanford has shown this process to be a lengthy process with EPA, so sufficient time needs to be allotted in a project schedule.

Table I-1 Federal and State RCRA Characteristic Hazardous Waste Codes Potentially Applicable to Hanford Tank Waste.

Waste Code	Description
D001*	Ignitable Waste
D002	Corrosive Waste
D003*	Reactive Waste
D004	Arsenic
D005	Barium
D006	Cadmium
D007	Chromium
D008	Lead
D009	Mercury
D010	Selenium
D011	Silver
D012*	Endrin (1,2,3,4,10,10-Hexachloro-1,7-Epoxy-1,4,4a,5,6,7,8,8a-Octahydro-1,4-Endo, Endo-5,8-Dimeth-Ano-Naphthalene)
D013*	Lindane (1,2,3,4,5,6-Hexa-Chlorocyclohexane, Gamma Isomer)
D014*	Methoxychlor (1,1,1-Trichloro-2,2-Bis [P-Methoxyphenyl] Ethane)
D015*	Toxaphene (C10 H10 Cl8, Technical Chlorinated Camphene, 67-69 Percent Chlorine)
D016*	2,4-D (2,4-Dichlorophenoxyacetic Acid)
D017*	2,4,5-Tp Silvex (2,4,5-Trichlorophenoxypropionic Acid)
D018	Benzene
D019	Carbon Tetrachloride
D020*	Chlordane
D021*	Chlorobenzene
D022	Chloroform
D023*	O-Cresol
D024*	M-Cresol
D025*	P-Cresol
D026*	Cresol
D027*	1,4-Dichlorobenzene
D028	1,2-Dichloroethane
D029	1,1-Dichloroethylene

D030	2,4-Dinitrotoluene
D031*	Heptachlor (And Its Epoxide)
D032*	Hexachlorobenzene
D033	Hexachlorobutadiene
D034	Hexachloroethane
D035	Methyl Ethyl Ketone
D036	Nitrobenzene
D037*	Pentachlorophenol
D038	Pyridine
D039	Tetrachloroethylene
D040	Trichlorethylene
D041	2,4,5-Trichlorophenol
D042*	2,4,6-Trichlorophenol
D043	Vinyl Chloride

**Identified on Hanford SST and DST Part A Hazardous Waste Permit, and DRAFT IDF Permit, but not identified as a tank waste code in current Integrated Disposal Facility permit (Rev. 8C)*

Table I-2 Federal and State RCRA Listed Hazardous Waste Codes Applicable to the Hanford Tank Waste.

Waste Code	**Description**
F001	The Following Spent Halogenated Solvents Used In Degreasing: Tetrachloroethylene, Trichlorethylene, Methylene Chloride, 1,1,1-Trichloroethane, Carbon Tetrachloride And Chlorinated Fluorocarbons; All Spent Solvent Mixtures/Blends Used In Degreasing Containing, Before Use, A Total Of Ten Percent Or More (By Volume) Of One Or More Of The Above Halogenated Solvents Or Those Solvents Listed In F002, F004, And F005; And Still Bottoms From The Recovery Of These Spent Solvents And Spent Solvent Mixtures.
F002	The Following Spent Halogenated Solvents: Tetrachloroethylene, Methylene Chloride, Trichloroethylene, 1,1,1-Trichloroethane, Chlorobenzene, 1,1,2-Trichloro-1,2,2-Trifluoroethane, Ortho-Dichlorobenzene, Trichlorofluoromethane, And 1,1,2, Trichloroethane; All Spent Solvent Mixtures/Blends Containing, Before Use, A Total Of Ten Percent Or More (By Volume) Of One Or More Of The Above Halogenated Solvents Or Those Solvents Listed In F001, F004, And F005; And Still Bottoms From The Recovery Of These Spent Solvents And Spent Solvent Mixtures.
F003	The Following Spent Nonhalogenated Solvents: Xylene, Acetone, Ethyl Acetate, Ethyl Benzene, Ethyl Ether, Methyl Isobutyl Ketone, N-Butyl Alcohol, Cyclohexanone, And Methanol; All Spent Solvent Mixtures/Blends Containing, Before Use, Only The Above Spent Nonhalogenated Solvents; And All Spent Solvent Mixtures/Blends Containing, Before Use, One Or More Of The Above Nonhalogenated Solvents, And A Total Of Ten Percent Or More (By Volume) Of One Or More Of Those Solvents Listed In F001, F002, F004, And F005; And Still Bottoms From The Recovery Of These Spent Solvents And Spent Solvent Mixtures.
F004	The Following Spent Nonhalogenated Solvents: Cresols, Cresylic Acid, And Nitrobenzene; And The Still Bottoms From The Recovery Of These Solvents; All Spent Solvent Mixtures/Blends Containing, Before Use, A Total Of Ten Percent Or More (By Volume) Of One Or More Of The Above Nonhalogenated Solvents Or Those Solvents Listed In F001, F002, And F005; And Still Bottoms From The Recovery Of These Spent Solvents And Spent Solvent Mixtures.
F005	The Following Spent Nonhalogenated Solvents: Toluene, Methyl Ethyl Ketone, Carbon Disulfide, Isobutanol, Pyridine, Benzene, 2-Ethoxyethanol, And 2-Nitropropane; All Spent Solvent Mixtures/Blends Containing, Before Use, A Total Of Ten Percent Or More (By Volume) Of One Or

	More Of The Above Nonhalogenated Solvents Or Those Solvents Listed In F001, F002, Or F004; And Still Bottoms From The Recovery Of These Spent Solvents And Spent Solvent Mixtures.
F006*	Wastewater Treatment Sludges From Electroplating Operations, Except From The Following Processes: (1) Sulfuric Acid Anodizing Of Aluminum; (2) Tin Plating On Carbon Steel; (3) Zinc Plating (Segregated Basis) On Carbon Steel; (4) Aluminum Or Zinc-Aluminum Plating On Carbon Steel; (5) Cleaning/Stripping Associated With Tin, Zinc, And Aluminum Plating On Carbon Steel; And (6) Chemical Etching And Milling Of Aluminum.
F007*	Spent Cyanide Plating Bath Solutions From Electroplating Operations.
F008*	Plating Bath Residues From The Bottom Of Plating Baths From Electroplating Operations In Which Cyanides Are Used In The Process.
F009*	Spent Stripping And Cleaning Bath Solutions From Electroplating Operations In Which Cyanides Are Used In The Process.
F010*	Quenching Bath Residues From Oil Baths From Metal Heat Treating Operations In Which Cyanides Are Used In The Process.
F011*	Spent Cyanide Solutions From Slat Bath Pot Cleaning From Metal Heat Treating Operations.
F012*	Quenching Wastewater Treatment Sludges From Metal Heat Treating Operations In Which Cyanides Are Used In The Process.
F028*	Residues Resulting From The Incineration Or Thermal Treatment Of Soil Contaminated With EPA Hazardous Waste Nos. F020, F021, F022, F023, F026, And F027.
F039	Leachate Resulting From The Treatment, Storage, Or Disposal Of Wastes Classified By More Than One Waste Code Under Subpart D, Or From A Mixture Of Wastes Classified Under Subparts C And D Of This Part. (Leachate Resulting From The Management Of One Or More Of The Following EPA Hazardous Wastes And No Other Hazardous Wastes Retains Its Hazardous Waste Code(S): F020, F021, F022, F023, F026, F027, And/or F028.)

**Identified on Hanford SST and DST Part A Hazardous Waste Permit, and DRAFT IDF Permit, but not identified as a tank waste code in current Integrated Disposal Facility permit (Rev. 8C)*

Table I-3 WA State-only Waste Codes Potentially Applicable to the Hanford Tank Waste.

Waste Code	**Description**
WP01	Persistent dangerous wastes, halogenated organic compounds, extremely hazardous wastes (EHW)
WP02	Persistent dangerous wastes, halogenated organic compounds, dangerous waste (DW)
WP03*	Persistent dangerous wastes, polycyclic aromatic hydrocarbons (EHW)
WT01	Toxic dangerous waste, extremely hazardous (EHW)
WT02	Toxic dangerous waste (DW)

**Identified on Hanford SST and DST Part A Hazardous Waste Permit, but not identified as a tank waste code in current State of Washington Dangerous Waste Codes or in the Integrated Disposal Facility permit (Rev. 8C)*

I.4 LAND DISPOSAL REQUIREMENTS APPLICABLE TO HANFORD TANK WASTE

Under RCRA, Hanford tank waste is categorized as non-wastewater and radioactive mixed waste subject to Land Disposal Restriction (LDR).[121] The tanks are considered a storage area for multiple upstream points of generation where the waste was originally produced.[122] The LDR program (established under 40 CFR Part 268) requires

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[121] Non-wastewater is defined as a waste that has both Total Suspended Solids (TSS) and Total Organic Carbon (TOC) greater than 1% by weight. Non-wastewaters are one of the two main treatability groups under RCRA in addition to wastewater.

[122] Winston, T.A.., 2013. HLVIT Applicability to Supplemental Immobilization: Impact of a RCRA New Point of Generation. RPP-RPT-52699, Rev.0.

treating hazardous waste or meeting specified levels for hazardous constituents before disposing of the waste on the land. EPA has established a treatment standard for each type of hazardous waste (given in Part 268, Subpart D). These standards are defined either as treatment technologies or contaminant concentration levels. The treatment standards are based on the performance of the best demonstrated available technology that reduces the toxicity and mobility of the hazardous waste.[123]

Vitrification of High Level Mixed Radioactive Waste (HLVIT) LDR standard was adopted by EPA in 1990 as a technology treatment standard for radioactive high level wastes generated during the reprocessing of fuel rods. Since the hazardous waste identification and LDR determinations are made at the point of generation under RCRA, EPA Region 10 and Ecology have determined that Hanford low activity waste is also subject to the HLVIT treatment standard as the high-level waste.[6] Since this treatment standard was established by the EPA for high-level wastes, it may be possible to determine an alternative course of action for the low activity waste portion of Hanford tank waste to comply with RCRA requirements to ensure safe management and disposal. For example, wastes that do not meet treatment standards may be considered for a variance, extension, exclusion, or no migration petition under RCRA. Figure K-1 represents an overall RCRA LDR flowchart identifying potential alternative paths for LDR compliance. For the low activity waste portion of Hanford's tank waste, prohibitions for on land disposal do not apply if an exemption is granted pursuant to a petition under 40 CFR Part 268.6. This petition, also referred to as "no-migration petition", if granted, would allow wastes to be placed in land disposal units without first meeting their treatment standards. The petition requires a demonstration that hazardous constituents will not migrate from a unit at concentrations greater than EPA-approved health-based levels. A no-migration variance may be granted for up to 10 years[124]. It should be noted that other sites within the DOE complex do not vitrify the low activity portion of their tank waste. These include the Savannah River Site and the West Valley Demonstration Project.

Under 40 CFR Part 268.44, it is also possible to petition EPA for a variance from a treatment standard (treatability variance) if the wastes cannot be treated to achieve the established treatment standard, or when the treatment standards are not appropriate. (Note – it is currently planned that the DOE will be submitting a treatability variance for both the high level and low level vitrified wasteforms that are planned to be produced at the WTP.) Wastes that may be eligible for a variance include the wastes that otherwise are different in physical or chemical properties from those wastes used to establish the treatment standard. This option does not exempt the waste, but instead establishes an alternative LDR treatment standard.

Another alternative to the existing standards is a determination of equivalent treatment (DET) under 40 CFR Part 268.42(b). An application to the Administrator can be submitted to demonstrate that an alternative treatment method can achieve a measure of performance equivalent to that achieved by the applicable treatment standards. In the case of Hanford low activity waste, this may require a demonstration of equivalent performance to vitrification. The submitted information must demonstrate that the alternative treatment method is in compliance with federal, state, and local requirements and is protective of human health and the environment.

In addition to the methods described above, the LAW fraction of Hanford waste may be eligible for recategorization as wastewater under 40 CFR Part 262.11(a). Under this requirement, the hazardous waste determination for each solid waste must be made at the point of waste generation, before any dilution, mixing, or other alteration of the waste occurs. However, if the waste has, or may have changed its properties in the

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[123] EPA, 2005. Introduction to Land Disposal Restrictions (40 CR Part 268). EPA530-K-013.

[124] A no-migration petition is not technically credible for onsite Hanford disposal where there is a direct pathway to groundwater. However, for an appropriate offsite disposal location, such as WCS, a no-migration petition may be technically credible.

course of the management of waste, RCRA classification of the waste may change as well. For Hanford tank waste such change may happen during the pretreatment process, i.e., the filtration and ion exchange process, where the tank waste is separated into its high activity and low activity portions per DOE O 435.1, resulting in LAW waste stream that may be considered wastewater.[125] This may be considered a "new point of generation" requiring a new determination of applicable RCRA waste codes and LDR standards.

In addition to HLVIT, some other RCRA concentration standards and Washington-state only standards are also applicable to Hanford tank wastes. Table I-4 lists all applicable LDR standards for Hanford tank waste.

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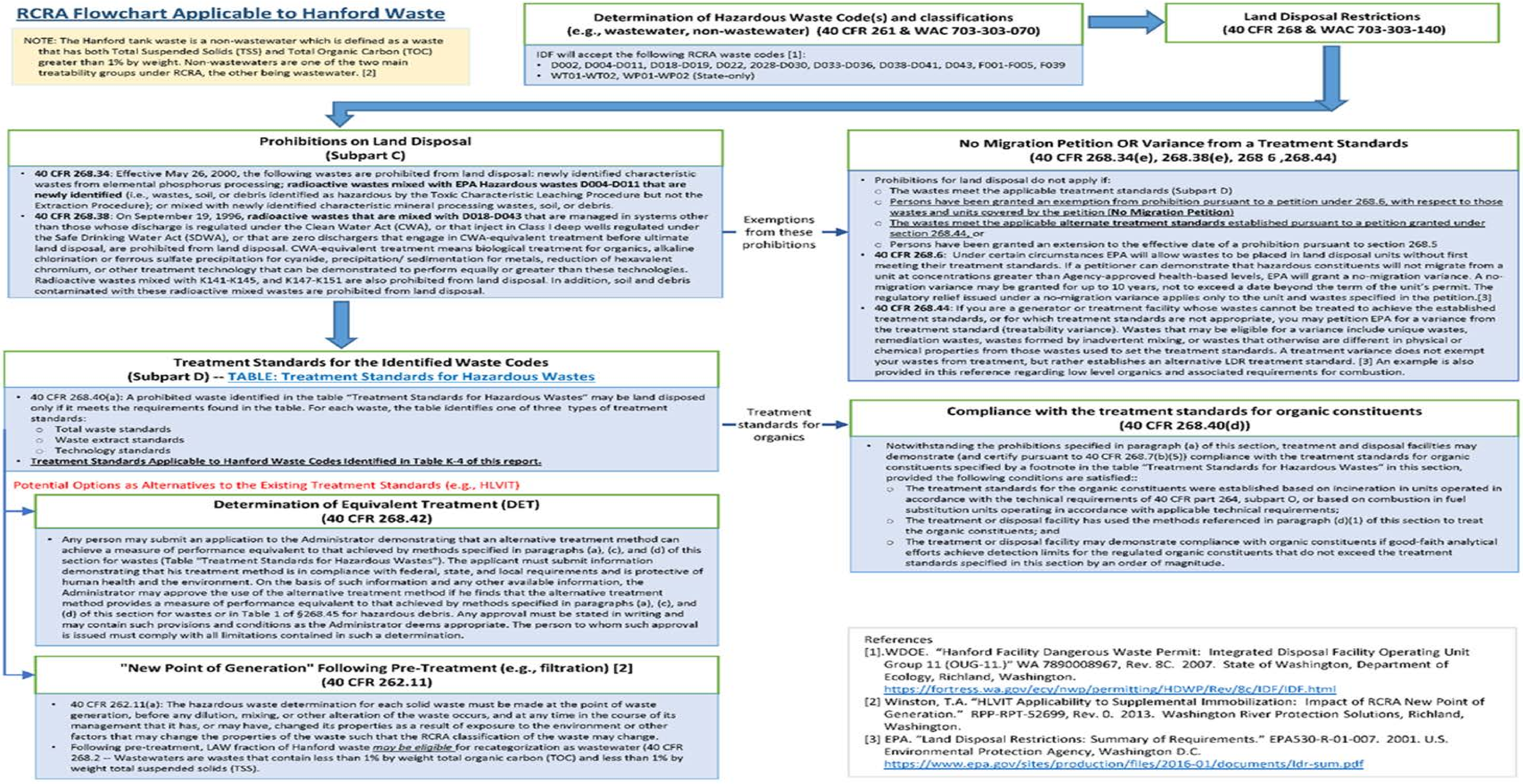
[125] Under 40 CFR 268.2, wastewaters are defined as wastes that contain less than 1% by weight total organic carbon (TOC) and less than 1 % by weight total suspended solids (TSS).



RCRA Flowchart Applicable to Hanford Waste

NOTE: The Hanford tank waste is a non-wastewater which is defined as a waste that has both Total Suspended Solids (TSS) and Total Organic Carbon (TOC) greater than 1% by weight. Non-wastewaters are one of the two main treatability groups under RCRA, the other being wastewater. [2]

Determination of Hazardous Waste Code(s) and classifications (e.g., wastewater, non-wastewater) (40 CFR 261 & WAC 703-303-070)

IDF will accept the following RCRA waste codes [1]:
- D002, D004-D011, D018-D019, D022, 2028-D030, D033-D036, D038-D041, D043, F001-F005, F039
- WT01-WT02, WP01-WP02 (State-only)

Land Disposal Restrictions (40 CFR 268 & WAC 703-303-140)

Prohibitions on Land Disposal (Subpart C)

- **40 CFR 268.34**: Effective May 26, 2000, the following wastes are prohibited from land disposal: newly identified characteristic wastes from elemental phosphorus processing; **radioactive wastes mixed with EPA Hazardous wastes D004-D011 that are newly identified** (i.e., wastes, soil, or debris identified as hazardous by the Toxic Characteristic Leaching Procedure but not the Extraction Procedure); or mixed with newly identified characteristic mineral processing wastes, soil, or debris.
- **40 CFR 268.38**: On September 19, 1996, **radioactive wastes that are mixed with D018-D043** that are managed in systems other than those whose discharge is regulated under the Clean Water Act (CWA), or that inject in Class I deep wells regulated under the Safe Drinking Water Act (SDWA), or that are zero dischargers that engage in CWA-equivalent treatment before ultimate land disposal, are prohibited from land disposal. CWA-equivalent treatment means biological treatment for organics, alkaline chlorination or ferrous sulfate precipitation for cyanide, precipitation/ sedimentation for metals, reduction of hexavalent chromium, or other treatment technology that can be demonstrated to perform equally or greater than these technologies. Radioactive wastes mixed with K141-K145, and K147-K151 are also prohibited from land disposal. In addition, soil and debris contaminated with these radioactive mixed wastes are prohibited from land disposal.

No Migration Petition OR Variance from a Treatment Standards (40 CFR 268.34(e), 268.38(e), 268 6 ,268.44)

- Prohibitions for land disposal do not apply if:
  - The wastes meet the applicable treatment standards (Subpart D)
  - Persons have been granted an exemption from prohibition pursuant to a petition under 268.6, with respect to those wastes and units covered by the petition (**No Migration Petition**)
  - The wastes meet the applicable **alternate treatment standards** established pursuant to a petition granted under section 268.44, or
  - Persons have been granted an extension to the effective date of a prohibition pursuant to section 268.5
- **40 CFR 268.6**: Under certain circumstances EPA will allow wastes to be placed in land disposal units without first meeting their treatment standards. If a petitioner can demonstrate that hazardous constituents will not migrate from a unit at concentrations greater than Agency-approved health-based levels, EPA will grant a no-migration variance. A no-migration variance may be granted for up to 10 years, not to exceed a date beyond the term of the unit's permit. The regulatory relief issued under a no-migration variance applies only to the unit and wastes specified in the petition.[3]
- **40 CFR 268.44**: If you are a generator or treatment facility whose wastes cannot be treated to achieve the established treatment standards, or for which treatment standards are not appropriate, you may petition EPA for a variance from the treatment standard (treatability variance). Wastes that may be eligible for a variance include unique wastes, remediation wastes, wastes formed by inadvertent mixing, or wastes that otherwise are different in physical or chemical properties from those wastes used to set the treatment standards. A treatment variance does not exempt your wastes from treatment, but rather establishes an alternative LDR treatment standard. [3] An example is also provided in this reference regarding low level organics and associated requirements for combustion.

Treatment Standards for the Identified Waste Codes (Subpart D) -- TABLE: Treatment Standards for Hazardous Wastes

- 40 CFR 268.40(a): A prohibited waste identified in the table "Treatment Standards for Hazardous Wastes" may be land disposed only if it meets the requirements found in the table. For each waste, the table identifies one of three types of treatment standards:
  - Total waste standards
  - Waste extract standards
  - Technology standards
- **Treatment Standards Applicable to Hanford Waste Codes Identified in Table K-4 of this report.**

Compliance with the treatment standards for organic constituents (40 CFR 268.40(d))

- Notwithstanding the prohibitions specified in paragraph (a) of this section, treatment and disposal facilities may demonstrate (and certify pursuant to 40 CFR 268.7(b)(5)) compliance with the treatment standards for organic constituents specified by a footnote in the table "Treatment Standards for Hazardous Wastes" in this section, provided the following conditions are satisfied::
  - The treatment standards for the organic constituents were established based on incineration in units operated in accordance with the technical requirements of 40 CFR part 264, subpart O, or based on combustion in fuel substitution units operating in accordance with applicable technical requirements;
  - The treatment or disposal facility has used the methods referenced in paragraph (d)(1) of this section to treat the organic constituents; and
  - The treatment or disposal facility may demonstrate compliance with organic constituents if good-faith analytical efforts achieve detection limits for the regulated organic constituents that do not exceed the treatment standards specified in this section by an order of magnitude.

Potential Options as Alternatives to the Existing Treatment Standards (e.g., HLVIT)

Determination of Equivalent Treatment (DET) (40 CFR 268.42)

- Any person may submit an application to the Administrator demonstrating that an alternative treatment method can achieve a measure of performance equivalent to that achieved by methods specified in paragraphs (a), (c), and (d) of this section for wastes (Table "Treatment Standards for Hazardous Wastes"). The applicant must submit information demonstrating that his treatment method is in compliance with federal, state, and local requirements and is protective of human health and the environment. On the basis of such information and any other available information, the Administrator may approve the use of the alternative treatment method if he finds that the alternative treatment method provides a measure of performance equivalent to that achieved by methods specified in paragraphs (a), (c), and (d) of this section for wastes or in Table 1 of §268.45 for hazardous debris. Any approval must be stated in writing and may contain such provisions and conditions as the Administrator deems appropriate. The person to whom such approval is issued must comply with all limitations contained in such a determination.

"New Point of Generation" Following Pre-Treatment (e.g., filtration) [2] (40 CFR 262.11)

- 40 CFR 262.11(a): The hazardous waste determination for each solid waste must be made at the point of waste generation, before any dilution, mixing, or other alteration of the waste occurs, and at any time in the course of its management that it has, or may have, changed its properties as a result of exposure to the environment or other factors that may change the properties of the waste such that the RCRA classification of the waste may change.
- Following pre-treatment, LAW fraction of Hanford waste *may be eligible* for recategorization as wastewater (40 CFR 268.2 -- Wastewaters are wastes that contain less than 1% by weight total organic carbon (TOC) and less than 1% by weight total suspended solids (TSS).

References

[1].WDOE. "Hanford Facility Dangerous Waste Permit: Integrated Disposal Facility Operating Unit Group 11 (OUG-11.)" WA 7890008967, Rev. 8C. 2007. State of Washington, Department of Ecology, Richland, Washington. https://fortress.wa.gov/ecy/nwp/permitting/HDWP/Rev/8c/IDF/IDF.html

[2] Winston, T.A. "HLVIT Applicability to Supplemental Immobilization: Impact of RCRA New Point of Generation." RPP-RPT-52699, Rev. 0. 2013. Washington River Protection Solutions, Richland, Washington.

[3] EPA. "Land Disposal Restrictions: Summary of Requirements." EPA530-R-01-007. 2001. U.S. Environmental Protection Agency, Washington D.C. https://www.epa.gov/sites/production/files/2016-01/documents/ldr-sum.pdf

Figure I-1. RCRA Flowchart Identifying Potential Paths for Compliance with Land Disposal Restrictions for Hanford LAW

I.5 REQUIREMENTS FOR AIR EMISSIONS

For the processing of the law activity waste at Hanford, toxic air pollutant controls under WA state regulations (WAC 173-460) apply.

The Clean Air Act is intended to protect and enhance the quality of the Nation‘s air resources so as to promote the public health and welfare and the productive capacity of its population. Section 118 of the Clean Air Act (42 U.S.C. 7401) requires each Federal agency with jurisdiction over any property or facility engaged in any activity that might result in the discharge of air pollutants to comply with all Federal, state, interstate, and local requirements‖ with regard to the control and abatement of air pollution.

Most of the provisions of the Washington Clean Air Act mirror the requirements of the Federal Clean Air Act. The Hanford Site Air Operating Permit (AOP) regulates emissions of criteria pollutants (WAC 173-400, "General Regulations for Air Pollution Sources"), toxic air pollutants (TAPs) (WAC 173-460, "Controls for New Sources of Toxic Air Pollutants"), and radioactive air pollutants (WAC 246-247, "Radiation Protection – Air Emissions") for all Hanford site sources. Hanford operates under state license No. FF-01.

Prior to beginning any work that would result in creating a new or modified source of airborne emissions, a Notice of Construction application must be submitted to the Washington State Departments of Health and Ecology for review and approval. Ensuring adequate emission controls, emissions monitoring/sampling, and/or annual reporting of air emissions is a typical requirement for radioactive air emission sources. A New Source Review is conducted by Ecology for toxic air pollutants and criteria pollutants emissions, or the WDOH Office of Radiation Protection for radioactive emissions.

Washington air regulations were recently revised to established requirements for determining the levels of dimethyl mercury (DMM) from emission sources, and to evaluate the potential exposures to humans and the environment from this contaminant. Dimethyl mercury is an organomercury compound that is very toxic to humans. A small skin exposure of a few drops has been. Dimethyl mercury is a colorless liquid that is volatile and insoluble in water. DMM has been identified in the Hanford tanks.

The regulations require that all projects with emissions of toxics, such as DMM, in Washington Administrative Code (WAC) 173-460-150 that exceeds the de minimis levels are required to submit a first tier review. If modeled ambient concentrations exceed the acceptable source impact levels (ASIL) in WAC 173-460-150 a second tier review or Health Impacts Analysis (HIA) is required. The primary purpose of the review is to document the analysis and evaluation of the potential human health related impacts of dimethyl mercury (DMM) emissions and offsite ambient concentrations from a proposed facility. The study is intended to determine if the DMM emissions from a facility will pose an unacceptable risk to the public from an emission source. Several HIAs have been submitted to Ecology for tank farm emission sources that documented no potential health or environmental impacts from those sources.

I.6 WASTEFORM PERFORMANCE REQUIREMENTS

Wasteform performance requirements for the immobilized LAW are defined principally by the enabling WIR criteria from DOE M 435.1-1, and waste acceptance criteria (WAC) of the disposal facility selected for final disposition of the immobilized LAW. Appendix F describes the two disposal facilities selected for consideration in this assessment, along with current regulatory , waste classification for disposal, and the two specific disposal sites considered in this analysis.

Table I-4 All LDR standards applicable for Hanford tank waste. Hanford characteristics waste codes are specified in the Hanford Tank Waste RCRA Part A permit application.

			Total Waste Standards	**Waste Extract Standards**	**Technology Standards**	
Constituent Common Name	**Description**	**CAS Number**	**Wastewater Standard, Concentration in (mg/l) [3]**	**Non-Wastewater Standard, Concentration in (mg/kg) unless noted as “mg/l TCLP” [5]**	**Non-Wastewater Standard, Technology Code**	
					Description	**Code**
Characteristic Wastes						
D001	Ignitability	NA	DEACT and meet 268.48 standards	DEACT and meet 268.48 standards	Ignitable Characteristic Wastes, except for the §261.21(a)(1) High TOC Subcategory. [> 10% TOC requires RORGS, CMBST, or POLYM]	DEACT and meet §268.48 standards ; or RORGS; or CMBST
D002	Corrosivity	NA	DEACT and meet 268.48 standards	DEACT and meet 268.48 standards	Radioactive high level wastes generated during the reprocessing of fuel rods. (Note: This subcategory consists of nonwastewaters only.)	HLVIT
D004	Arsenic	7440-38-2	1.4 and meet 268.48 standards	5.0 mg/l TCLP and meet 268.48 standards		
D005	Barium	7440-39-3	1.2 and meet 268.48 standards	21 mg/l TCLP and meet		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
Constituent Common Name	Description	CAS Number	Wastewater Standard, Concentration in (mg/l) [3]	Non-Wastewater Standard, Concentration in (mg/kg) unless noted as "mg/l TCLP" [5]	Non-Wastewater Standard, Technology Code	
					Description	Code
				268.48 standards		
D006	Cadmium	7440-43-9	0.69 and meet 268.48 standards	0.11 mg/l TCLP and meet 268.48 standards		
D007	Chromium	7440-47-3	2.77 and meet 268.48 standards	0.60 mg/l TCLP and meet 268.48 standards		
D008	Lead	7439-92-1	0.69 and meet 268.48 standards	0.75 mg/l TCLP and meet 268.48 standards		
D009	Mercury	7439-97-6	0.15 mg/l TCLP and meet 268.48 standards	0.025 mg/l TCLP and meet 268.48 standards		
D010	Selenium	7782-49-2	0.82 and meet 268.48 standards	5.7 mg/l TCLP and meet 268.48 standards		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
Constituent Common Name	Description	CAS Number	Wastewater Standard, Concentration in (mg/l) [3]	Non-Wastewater Standard, Concentration in (mg/kg) unless noted as "mg/l TCLP" [5]	Non-Wastewater Standard, Technology Code	
					Description	Code
D011	Silver	7440-22-4	0.43 and meet 268.48 standards	0.14 mg/l TCLP and meet 268.48 standards		
D018	Benzene	71-43-2	0.14 and meet 268.48 standards	10 and meet 268.48 standards	N/A	N/A
D019	Carbon Tetrachloride	56-23-5	0.057 and meet 268.48 standards	6.0 and meet 268.48 standards	N/A	N/A
D022	Chloroform	67-66-3	0.046 and meet 268.48 standards	6.0 and meet 268.48 standards	N/A	N/A
D028	1,2-dichloroethane	107-06-2	0.21 and meet 268.48 standards	6.0 and meet 268.48 standards	N/A	N/A
D029	1,1-dichloroethylene	75-35-4	0.025 and meet 268.48 standards	6.0 and meet 268.48 standards	N/A	N/A
D030	2,4-dinitrotoluene	121-14-12	0.32 and meet 268.48 standards	140 and meet 268.48 standards	N/A	N/A

			Total Waste Standards	Waste Extract Standards	Technology Standards	
Constituent Common Name	Description	CAS Number	Wastewater Standard, Concentration in (mg/l) [3]	Non-Wastewater Standard, Concentration in (mg/kg) unless noted as "mg/l TCLP" [5]	Non-Wastewater Standard, Technology Code	
					Description	Code
D033	Hexachlorobutadiene	87-68-3	0.055 and meet 268.48 standards	5.6 and meet 268.48 standards	N/A	N/A
D034	Hexachloroethane	67-72-1	0.055 and meet 268.48 standards	30 and meet 268.48 standards	N/A	N/A
D035	Methyl ethyl ketone	78-93-3	0.28 and meet 268.48 standards	36 and meet 268.48 standards	N/A	N/A
D036	Nitrobenzene	98-95-3	0.068 and meet 268.48 standards	14 and meet 268.48 standards	N/A	N/A
D038	Pyridine	110-86-1	0.014 and meet 268.48 standards	16 and meet 268.48 standards	N/A	N/A
D039	Tetrachloroethylene	127-18-4	0.056 and meet 268.48 standards	6.0 and meet 268.48 standards	N/A	N/A
D040	Trichloroethylene	79-01-6	0.054 and meet 268.48 standards	6.0 and meet 268.48 standards	N/A	N/A
D041	2,4,5 Tricholorophenol	95-95-4	0.18 and meet 268.48 standards	7.4 and meet 268.48 standards	N/A	N/A

			Total Waste Standards	Waste Extract Standards	Technology Standards	
Constituent Common Name	**Description**	**CAS Number**	**Wastewater Standard, Concentration in (mg/l) [3]**	**Non-Wastewater Standard, Concentration in (mg/kg) unless noted as "mg/l TCLP" [5]**	**Non-Wastewater Standard, Technology Code**	
					Description	**Code**
D043	Vinyl Chloride	75-01-4	0.27 and meet 268.48 standards	6.0 and meet 268.48 standards	N/A	N/A
WT01 (Washington State-only) - Toxic Dangerous Waste – Extremely Hazardous Waste		NA	No numerical or concentration standard	No numerical or concentration standard		
WT02 (Washington State-only) - Toxic Dangerous Waste		NA	No numerical or concentration standard	No numerical or concentration standard		
WP01 (Washington State-only) - Persistent Dangerous Waste – Halogenated Organic Compound – Extremely Hazardous Waste		NA	No numerical or concentration standard	No numerical or concentration standard		
WP02 (Washington State- only) - Persistent Dangerous Waste – Halogenated Organic Compound		NA	No numerical or concentration standard	No numerical or concentration standard		
F001-F005 Waste Constituents that are not duplicated in the DXXX Characteristic Wastes						

			Total Waste Standards	**Waste Extract Standards**	**Technology Standards**	
Constituent Common Name	**Description**	**CAS Number**	**Wastewater Standard, Concentration in (mg/l)**[3]	**Non-Wastewater Standard, Concentration in (mg/kg) unless noted as "mg/l TCLP"**[5]	**Non-Wastewater Standard, Technology Code**	
					Description	**Code**
Acetone		67-64-1	0.28	160		
n-Butyl alcohol		71-36-3	5.6	2.6		
Carbon disulfide		75-15-0	3.8	4.8 mg/l TCLP[b]		
Chlorobenzene		108-90-7	0.057	6.0		
o-Cresol		95-48-7	0.11	5.6		
m-Cresol		108-39-4	0.77	5.6		
p-Cresol		106-44-5	0.77	5.6		
Cresol – mixed isomers		1319-77-3	0.88	11.2		
Cyclohexanone		108-94-1	0.36	0.75 mg/l TCLP[b]		
o-Dichlorobenzene		95-50-1	0.088	6.0		
Ethyl Acetate		141-78-6	0.34	33		
Ethyl Benzene		100-41-4	0.057	10		
Ethyl ether		60-29-7	0.12	160		
Isobutyl alcohol		78-83-1	5.6	170		
Methanol		67-56-1	5.6	0.75 mg/l TCLP[b]		
Methylene chloride		75-9-2	0.089	30		
Methyl isobutyl ketone		108-10-1	0.14	33		
Toluene		108-88-3	0.080	10		
1,1,1-Trichloroethane		71-55-6	0.054	6.0		
1,1,2-Trichloroethane		79-00-5	0.054	6.0		
1,1,2-Trichloro-1,1,2- trifluoroethane		76-13-1	0.057	30		

			Total Waste Standards	**Waste Extract Standards**	**Technology Standards**	
					Non-Wastewater Standard, Technology Code	
Constituent Common Name	**Description**	**CAS Number**	**Wastewater Standard, Concentration in (mg/l) [3]**	**Non-Wastewater Standard, Concentration in (mg/kg) unless noted as "mg/l TCLP" [5]**	**Description**	**Code**
Trichloromonofluoromethane		75-69-4	0.020	30		
Xylenes – mixed isomers		1330-20-7	0.32	30		
2-Nitropropane [c]		79-46-9	(WETOX or CHOXD) fb CARBN or CMBST c	CMBST [c]		CMBST [c]
2-Ethoxyethanol [d]		110-80-5	BIODG; or CMBST [d]	CMBST [d]		CMBST [d]
UHCs that are not duplicated in characteristic or listed wastes						
1,1,1,2-Tetrachloroethane		630-20-6	0.057	6.0		
1,1,2,2-Tetrachloroethane		79-34-5	0.057	6.0		
1,1-Dichloroethane		75-34-3	0.059	6.0		
1,2,4-Trichlorobenzene		120-82-1	0.055	19		
1,2-Dichloropropane		78-87-5	0.85	18		
1 ,2-trans-Dichloroethene		156-60-5	0.054	30		
1,3-Dichlorobenzene		541-73-1	0.036	6.0		
1,4-Dichlorobenzene		106-46-7	0.090	6.0		
l,4-Dioxane		123-91-1	12.0	170		
2,3,4,6-Tetrachlorophenol		58-90-2	0.030	7.4		
2,4,6-Trichlorophenol		88-06-2	0.035	7.4		
2,4-Dichlorophenol		120-83-2	0.044	14		
2-Chloronaphthalene		91-58-7	0.055	5.6		
2-Chlorophenol		95-57-8	0.044	5.7		

			Total Waste Standards	**Waste Extract Standards**	**Technology Standards**	
Constituent Common Name	**Description**	**CAS Number**	**Wastewater Standard, Concentration in (mg/l)** [3]	**Non-Wastewater Standard, Concentration in (mg/kg) unless noted as “mg/l TCLP”** [5]	**Non-Wastewater Standard, Technology Code**	
					Description	**Code**
2-Methyl-2-propenenitrile		126-98-7	0.24	84		
2-Nitrophenol		88-75-5	0.028	13		
2-sec-Butyl-4,6- dinitrophenol (dinoseb)		88-85-7	0.066	2.5		
3-Chloropropene		107-05-1	0.036	30		
3-Methy1cholanthrene		56-49-5	0.0055	15		
4-Bromophenylphenyl ether		101-55-3	0.055	15		
4-Chloro-3-methy1pheno1		59-50-7	0.018	14		
Acenaphthene		83-32-9	0.059	3.4		
Acenaphthylene		208-96-8	0.059	3.4		
Acetonitrile		75-05-8	5.6	38		
Acetophenone		98-86-2	0.010	9.7		
Acrolein		107-02-8	0.061	NA		
Acrylonitrile		107-13-1	0.24	84		
Alpha-BHC		319-84-6	0.00014	0.066		
Anthracene		120-12-7	0.059	3.4		
Antimony		7440-36-0	1.9	1.15 mg/l TCLP		
Benzo(a)anthracene		56-55-3	0.059	3.4		
Benzo(a)pyrene		50-32-8	0.061	3.4		
Benzo(b) fluoranthene		205-99-2	0.11	6.8		
Benzo(ghi)pery1ene		191-24-2	0.0055	1.8		
Benzo(k)fluoranthene		207-08-9	0.11	6.8		
Beryllium		7440-41-7	0.82	1.22 mg/l TCLP		

			Total Waste Standards	**Waste Extract Standards**	**Technology Standards**	
Constituent Common Name	**Description**	**CAS Number**	**Wastewater Standard, Concentration in (mg/l) [3]**	**Non-Wastewater Standard, Concentration in (mg/kg) unless noted as "mg/l TCLP" [5]**	**Non-Wastewater Standard, Technology Code**	
					Description	**Code**
Beta-BHC		319-85-7	0.00014	0.066		
Bis(2-ethylhexyl) phthalate		117-81-7	0.28	28		
Bromodichloromethane		75-27-4	0.35	15		
Bromomethane		74-83-9	0.11	15		
Butylbenzylphthalate		85-68-7	0.017	28		
Chloroethane		75-00-3	0.27	6.0		
Chloromethane		74-87-3	0.19	30		
Cresols (total) – substituted for each cresols isomer		1319-77-3	0.11/0.77	5.6		
Chrysene		218-01-9	0.059	3.4		
cis-l,3-dichloropropene		10061-01-5	0.036	18		
Cyanide (amenable)		57-12-5	0.86	30		
Cyanide (total)		57-12-5	1.2	590		
delta-BHC		319-86-8	0.023	0.066		
Dibenz[a,h] anthracene		53-70-3	0.055	8.2		
Dibenz (a,e) pyrene		192-65-4	0.061	NA		
Dichlorodifluoromethane		75-71-8	0.23	7.2		
Diethyl phthalate		84-66-2	0.20	28		
Di-n-butylphthalate		84-74-2	0.057	28		
Di-n-octylphthalate		117-84-0	0.017	28		
Ethylene dibromide		106-93-4	0.028	15		
Fluoranthene		206-44-0	0.068	3.4		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
					Non-Wastewater Standard, Technology Code	
Constituent Common Name	Description	CAS Number	Wastewater Standard, Concentration in (mg/l) [3]	Non-Wastewater Standard, Concentration in (mg/kg) unless noted as "mg/l TCLP" [5]	Description	Code
Fluorene		86-73-7	0.059	3.4		
gamma-BHC (Lindane)		58-89-9	0.0017	0.066		
Indeno(1 ,2,3-cd)pyrene		193-39-5	0.0055	3.4		
Isodrin		465-73-6	0.021	0.066		
N,N-diphenylamine		122-39-4	0.92	13		
Naphthalene		91-20-3	0.059	5.6		
Nickel		7440-02-0	3.98	11 mg/l TCLP		
N -nitroso-di-N - propylamine		621-64-7	0.40	14		
N-nitrosomorpholine		59-89-2	0.40	2.3		
N-nitroso-N,N- dimethylamine		62-75-9	0.40	2.3		
Pentachloronitrobenzene (PCNB)		82-68-8	0.055	4.8		
Phenanthrene		85-01-8	0.059	5.6		
Phenol		108-95-2	0.039	6.2		
Polychlorinated biphenyls (PCBs)		1336-36-3	0.10	10		
p-phthalic acid		100-21-0	0.055	28		
Propionitrile		107-12-0	0.24	360		
Pyrene		129-00-0	0.067	8.2		
Silvex (2,4,5-TP)		93-72-1	0.72	7.9		
Tetrachlorodibenzo-p- dioxin (2,3,7,8-)		41903-57-5	0.000063	0.001		
Thallium		7440-28-0	1.4	0.20 mg/l TCLP		
trans-l,3-Dichloropropene		10061-02-6	0.036	18		

CAS = Chemical Abstract Service

[a] During the Regulatory Data Quality Objectives Process, 2,4-dinitrotoluene was removed from the list of contaminants of concern due to use unrelated to Hanford. Nevertheless, as long as it remains in the Hanford Tank Waste Part A application it should remain as an applicable standard.

[b] This standard is only applicable to F003 and/or F005 solvent wastes that contain any combination of one or more of the following three solvents as the only F001-F005 solvents: carbon disulfide, cyclohexanone, and methanol.

[c] This standard is only applicable to F005 solvent waste containing 2-Nitropropane as the only listed F001-F005 solvent. During the Regulatory Data Quality Objectives Process this constituent was removed from the list of contaminants of concern due to use unrelated to Hanford.

[d] This standard is only applicable to F005 solvent waste containing 2-Ethoxyethenol as the only F001-5 solvent. During the Regulatory Data Quality Objectives Process this constituent was removed from the list of contaminants of concern due to use unrelated *to Hanford* [sic]

3 - (from original 268.40 Table). Concentration standards for wastewaters are expressed in mg/L and are based on analysis of composite samples.

5 - (from original 268.40 Table). Except for Metals (EP or TCLP) and Cyanides (Total and Amenable) the non-wastewater treatment standards expressed as a concentration were established, in part, based upon incineration in units operated in accordance with the technical requirements of 40 CFR Part 264 Subpart O or Part 265 Subpart O, or based upon combustion in fuel substitution units operating in accordance with applicable technical requirements. A facility may comply with these treatment standards according to provisions in 40 CFR 268.40(d). All concentration standards for non-wastewaters are based on analysis of grab samples.

I.7 REFERENCES

Ref. 1 -- Resource Conservation and Recovery Act of 1976 (RCRA), U.S. Environmental Protection Agency, Washington, D.C.
Ref. 2 -- WAC 173-303, “Dangerous Waste Regulations,” Washington Administrative Code, as amended.
Ref 3 -- 40 CFR 61, “National Emission Standards for Hazardous Air Pollutants,” Code of Federal Regulations, as amended.
Ref. 4 -- WAC 173-400, “General Regulations for Air Pollution Sources,” Washington Administrative Code, as amended.
Ref. 5 -- WAC 173-460, “Controls for New Sources of Toxic Air Pollutants,” Washington Administrative Code, as amended.
Ref. 6 -- WAC 246-247, “Radiation Protection – Air Emissions,” Washington Administrative Code, as amended.
Ref. 7 -- 40 CFR 761, *Polychlorinated Biphenyls (PCBs) Manufacturing, Processing, Distribution in Commerce, and Use Prohibitions.*
Ref. 8 -- DOE M 435.1-1, Chg 2, 2011, Radioactive Waste Management Manual, U.S. Department of Energy, Washington, D.C.
Ref. 9 -- WA 7890008967, 2007, “Hanford Facility Dangerous Waste Permit,” Rev. 8C, State of Washington, Department of Ecology, Richland, Washington.
Ref. 10 -- U.S. EPA, Region 10, *Framework Agreement for Management of Polychlorinated Biphenyls (PCBs) in Hanford Tank Waste*, August 31, 2000.
Ref. 11 -- U. S. DOE, “*Transmittal of Toxic Substance Control Act (TSCA) Risk-Based Disposal Application for the Double Shell Tank (DST) System for 2001*,” January 15, 2002.
Ref. 12 -- U.S. DOE, “*Application for Risk-Based Disposal Approval for PCBs Hanford 200 Area Liquid Waste Processing Facilities*”, February 28, 20002

APPENDIX J. FEED VECTOR

J.1 SUMMARY

The Hanford Waste Treatment and Immobilization Plant (WTP) is a complex of facilities[4] designed to receive waste from the storage tanks and perform all pretreatment processes to prepare the waste for immobilization and then immobilize the waste in borosilicate glass[5]. A simplified diagram showing the tank farm, WTP, and other facilities required is shown in Figure J-1.

The Supplemental Low Activity Waste (LAW) mission/scope is defined by the One System Integrated Flowsheet as immobilization of excess treated LAW supernate once the full capacity of the current LAW facility is exceeded. The excess supernate is generated because the amount of LAW supernate needed to transfer high level waste (HLW) to the WTP combined with the supernate generated during HLW pretreatment (washing and leaching operations) along with the supernate needing treatment from the tank farms is greater than the capacity of the current LAW vitrification facility. If the WTP processing were adjusted to not exceed the LAW capacity, then HLW processing would be reduced and the overall mission length would be extended.

The SLAW facility is expected to receive feed from two sources: the Low Activity Waste Pretreatment System (LAWPS) and the WTP Pretreatment (PT) facility. The feed vectors from each source have been estimated by the One System Integrated Flowsheet. The technology for immobilization has not been formally designated, but vitrification is assumed to be the baseline in the Integrated Flowsheet with grout considered as an option. SLAW is assumed to receive the LAW from the LAWPS and PT, immobilize the LAW, package and ship the waste to a disposal facility, and internally handle any secondary wastes that require treatment prior to disposal.

Process flows greatly simplified
Dilute LAW feed can be sent to evaporation, not shown
Evaporator condensate is sent to LERF/ETF, not shown for all evaporators
Solid secondary waste stream only shown for PT, applies to all facilities

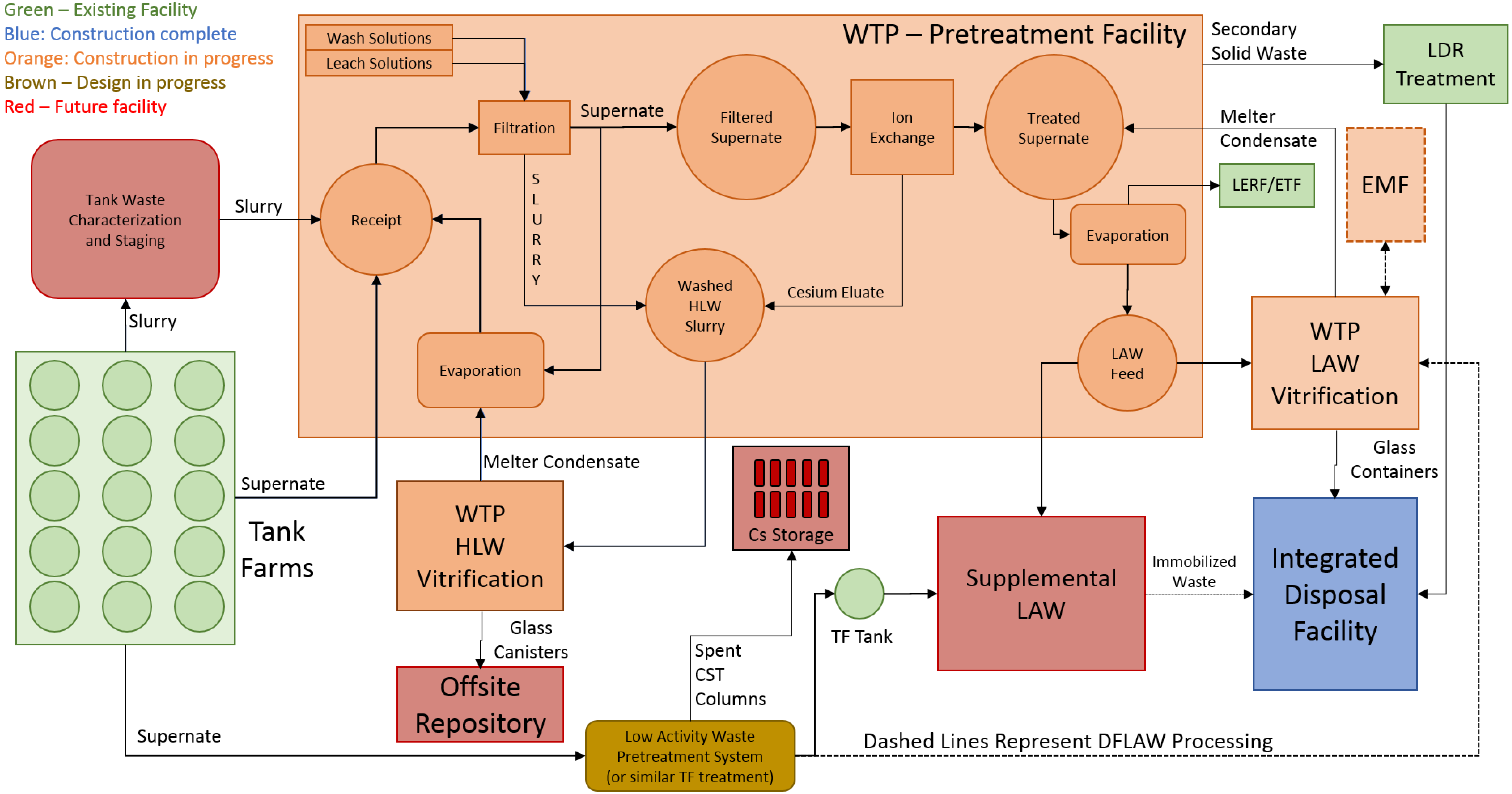


Figure J-1. Simplified Flowsheet for Immobilization of Hanford Waste during Full WTP Operation

J.2 PROCESSES FOR LAW IMMOBILIZATION AND SLAW IMMOBILIZATION

J.2.1 Hanford Waste Background

The Hanford site generated millions of gallons of radioactive waste during production of nuclear materials. A number of different chemical processes were used at Hanford to separate and purify plutonium, including the Bismuth Phosphate, REDuction and OXidation (REDOX), and Plutonium Uranium Extraction (PUREX) processes. In addition to the separation processes, cesium removal and other treatment processes were performed on the tank waste. As a result of the varied processes performed, the wastes stored at Hanford vary significantly in chemical and radionuclide content, although some incidental blending of the various wastes has occurred during storage[1].

The waste has been stored in 177 underground, carbon steel storage tanks. Many of these tanks are known to have developed leaks[2]; therefore, many tanks were treated to eliminate free liquid to the extent possible. The issues with the known leaks and the age of the storage tanks have led to restrictions on the type of processing allowed in the tank farms[3].

J.2.2 Baseline

The Hanford Waste Treatment and Immobilization Plant (WTP) is a complex of facilities[4] designed to receive waste from the storage tanks and perform all pretreatment processes to prepare the waste for immobilization and then immobilize the waste in borosilicate glass[5].

The tank waste will be separated into supernate and slurry in the tank farm by allowing solids to settle, then decanting supernate. Slurries will be transferred to a characterization facility to allow representative samples to be taken and any size reduction of the solids to be performed prior to transfer to the PT. Supernate from the tank farms will be transferred directly to PT or the LAWPS.

In PT, the supernate is combined with evaporated recycle (the supernate can also be sent to evaporation), and then with the slurry. Filtration is performed to separate the solids from supernate; then the concentrated solids slurry is “washed” to reduce the amount of soluble species in the slurry and can be chemically leached to remove aluminum and chromium. The solids slurry (along with the cesium extracted from the supernate) is combined with glass-former chemicals and vitrified to form a borosilicate glass in the WTP High Level Waste (HLW) facility. Canisters of the HLW will eventually be transferred to a geologic repository.

Spent wash solutions are combined with the filtered supernate, while spent leach solutions are transferred to the evaporator and recycled to the receipt process. The filtered supernate is treated to remove cesium using an ion exchange process, then combined with melter condensate from the LAW vitrification facility. After concentration by evaporation, the treated supernate is transferred to the LAW facility for immobilization in borosilicate glass.

When the amount of LAW supernate generated is greater than can be processed by the LAW facility, the excess is sent to SLAW for immobilization. It is currently estimated that approximately 1/2 of the treated supernate will be sent to SLAW. It should be noted that the excess supernate is generated as a result of processing sufficient HLW to operate the HLW vitrification facility at capacity as supernate is required to retrieve and transfer the HLW solids to WTP and additional supernate is generated during solids washing and leaching operations.

The LAW facility utilizes two melters with a capacity of 30 metric tons per day to immobilize the treated supernate in borosilicate glass. The glass containers generated will be sent to the Integrated Disposal Facility (IDF) on the Hanford site. The melter offgas system condenses the water evaporated by the melter and recycles the condensate along with any particulates scrubbed from the offgas stream back to PT.

The tank farm is predicted to be able to supply more supernate than the PT can process during portions of the immobilization mission. This supernate is sent to the TSCR/LAWPS facility to remove solids and cesium (using filtration and ion exchange similar to PT) with the treated supernate sent to SLAW.

J.2.3 Direct Feed Options

The TSCR/LAWPS facility is expected to start operation prior to PT and will feed LAW vitrification until PT is started. Melter condensate will be handled by the Effluent Management Facility (EMF) during direct feeding of LAW from the LAWPS.

J.2.3.1 Baseline SLAW Process

A decision on the immobilization technology for SLAW has not been finalized; as stated in the Integrated Flowsheet, "the LAW supplemental treatment facility is assumed to be either a second LAW vitrification facility or a grout facility"[6]. The Integrated Flowsheet defines the function of SLAW as immobilization of excess treated LAW supernate after the capacity of the existing LAW facility is met. Preliminary estimates for immobilized waste volume are performed in the Integrated Flowsheet for both the vitrification and grout options.

The SLAW facility has two feed vectors in the current baseline flowsheet: Leftover LAW from PT and additional feed from LAWPS[7]. SLAW is treated as a "black box" in the current flowsheet, meaning that no criteria have been set for minimum or maximum flow, etc. and that any material treated to the requirements for the LAW vitrification facility can be treated at SLAW. SLAW is also assumed to be a complete treatment facility with no returns of secondary waste to any WTP facility. Secondary liquid waste (condensate) is sent to the Liquid Effluent Retention Facility / Effluent Treatment Facility (LERF/ETF). Solid secondary waste is sent to the Land Disposal Restrictions (LDR) treatment facility to be treated by encapsulation in grout for onsite land disposal. The immobilized waste from SLAW is assumed to be disposed at the IDF, but a final decision has not been made.

The interfaces between SLAW and other facilities are described in Table J-1and shown in Figure J-2, based on the assumptions made in the One System Integrated Flowsheet[6]. These interfaces would change depending on the options chosen; for example, a grout facility would not be expected to generate a condensate stream to be treated at LERF/ETF. It is noted that the capacity of the LERF-ETF facility to treat the volume of waste water generated by SLAW would require upgrades to the facility, but these upgrades are assumed to be performed in System Plan 8 and are outside the scope of this evaluation.

Table J-1. SLAW Interfaces

Stream	Description
45	Treated LAW Feed to SLAW from PT
46	Treated LAW Feed to SLAW from LAWPS
47	Stack Exhaust from SLAW
48	Liquid secondary waste from SLAW to LERF/ETF
49	Immobilized LAW to IDF
79	Solid secondary waste to a facility to treat waste to permit disposal

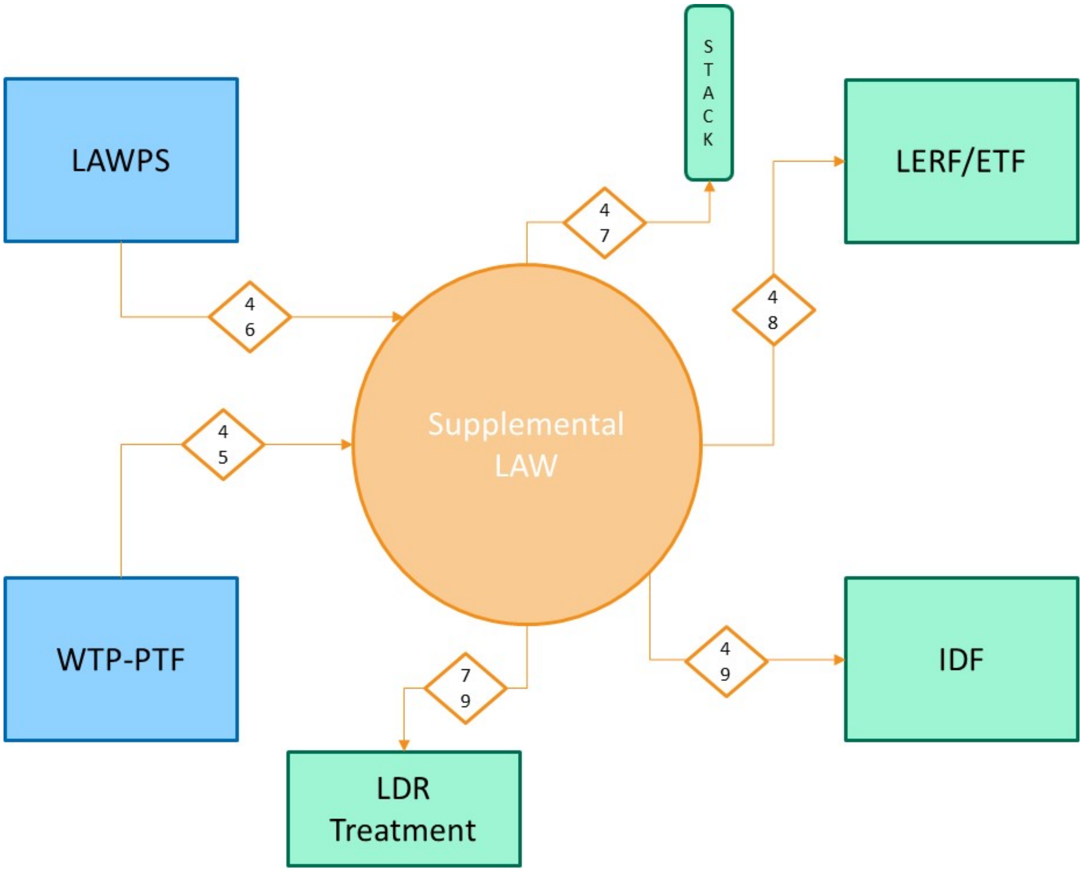


Figure J-2. SLAW Detail: Interfaces

J.2.3.2 SLAW Feed Vector

The SLAW feed vector [7] calculated for the One System River Protection Project Integrated Flowsheet [6] is being used in the evaluation of the feasibility of proposed SLAW processes. This feed vector represents any remaining LAW supernate generated by PT and LAWPS processes after the existing WTP LAW vitrification facility reaches maximum capacity with no constraints on volumetric flow.

This feed vector represents the only current information available for the streams assumed to be processed through SLAW facility. The feed vector provided represents a single model run of the Integrated Flowsheet. The flowsheet is updated routinely by the One System Organization and calculates all process streams that will be generated during immobilization of Hanford tank wastes. The flowsheet includes the retrieval processes in the Hanford tank farms, processing through pretreatment facilities, and final wasteform generation as well as estimates for secondary waste stream generation.

The assumptions made during flowsheet model run (including tank farm retrieval sequencing, selection of feeds for LAWPS processing, etc.) significantly impact the results. In addition, the values in the feed vector represent monthly averages versus batch by batch processing. Therefore, while the SLAW feed vector is the best currently available, the actual waste processed through SLAW could be significantly different that the values shown.

The varied methods used during the nuclear material separations processing at Hanford resulted in waste that varies significantly in composition. Typically, these varying waste types are segregated across the tank farms (although some incidental blending has occurred and will occur during retrieval) which can result in large swings in feed composition to the SLAW facility, as shown in Figure J-3, Figure J-4, Figure J-5, and Figure J-6. Thus, any

SLAW process would have to accommodate the expected extremes in waste feed compositions as sufficient lag storage is not expected to be provided to smooth these peaks. These compositional extremes are further exacerbated by the differences in sodium concentrations in the feed to SLAW from the PT facility (~8M) versus the LAWPS facility (~5.6M) as well as the inclusion of the LAW vitrification facility recycles in the feed from PT. The feed from PT to the LAW facility is identical in composition to the stream feed to the LAW vitrification facility[6] from PT in the Integrated Flowsheet.

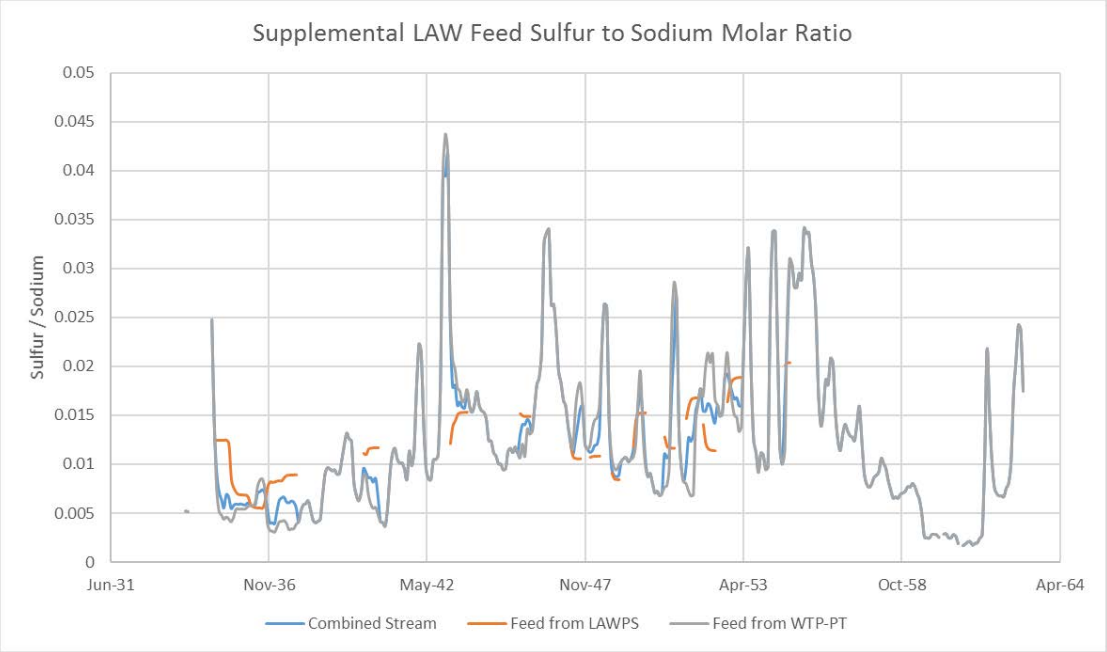


Figure J-3. Sulfur to Sodium Ratio

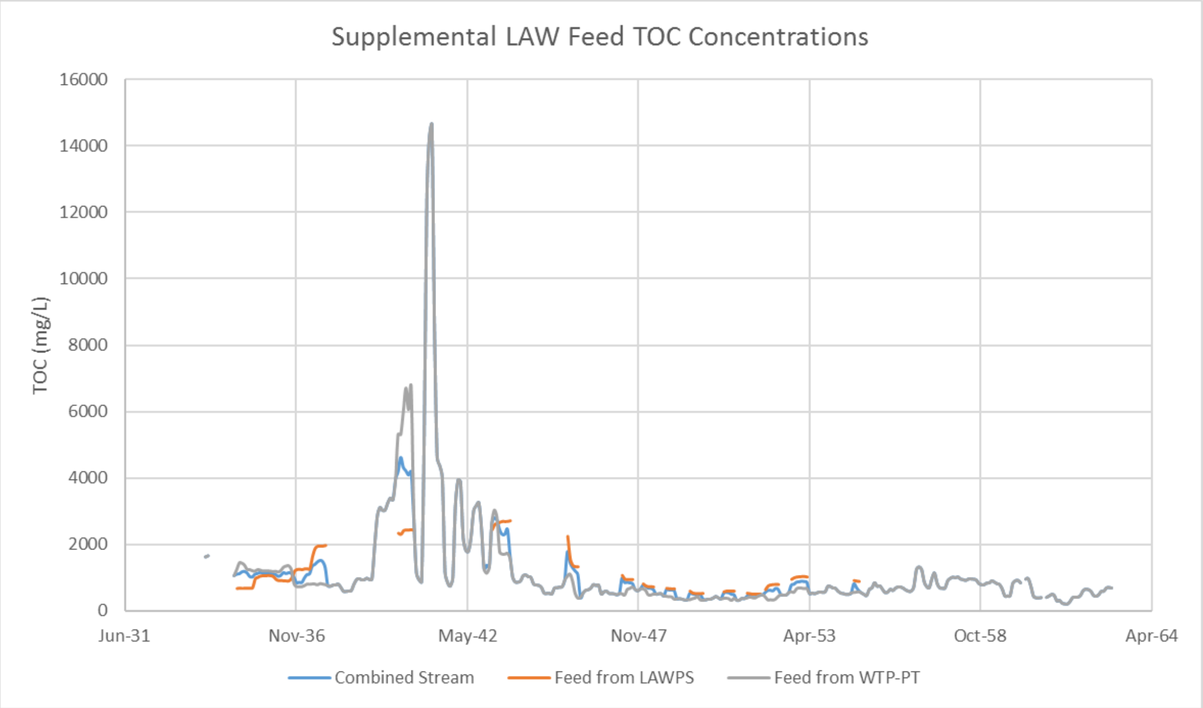


Figure J-4. TOC Concentration

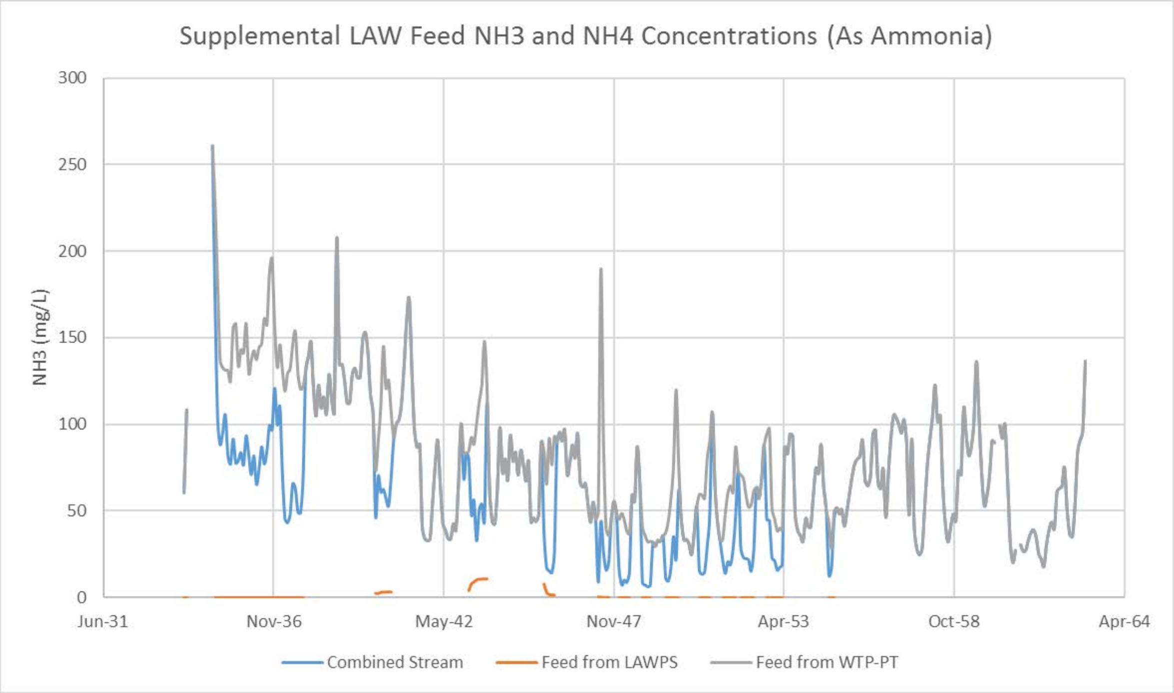


Figure J-5. Ammonia Concentration

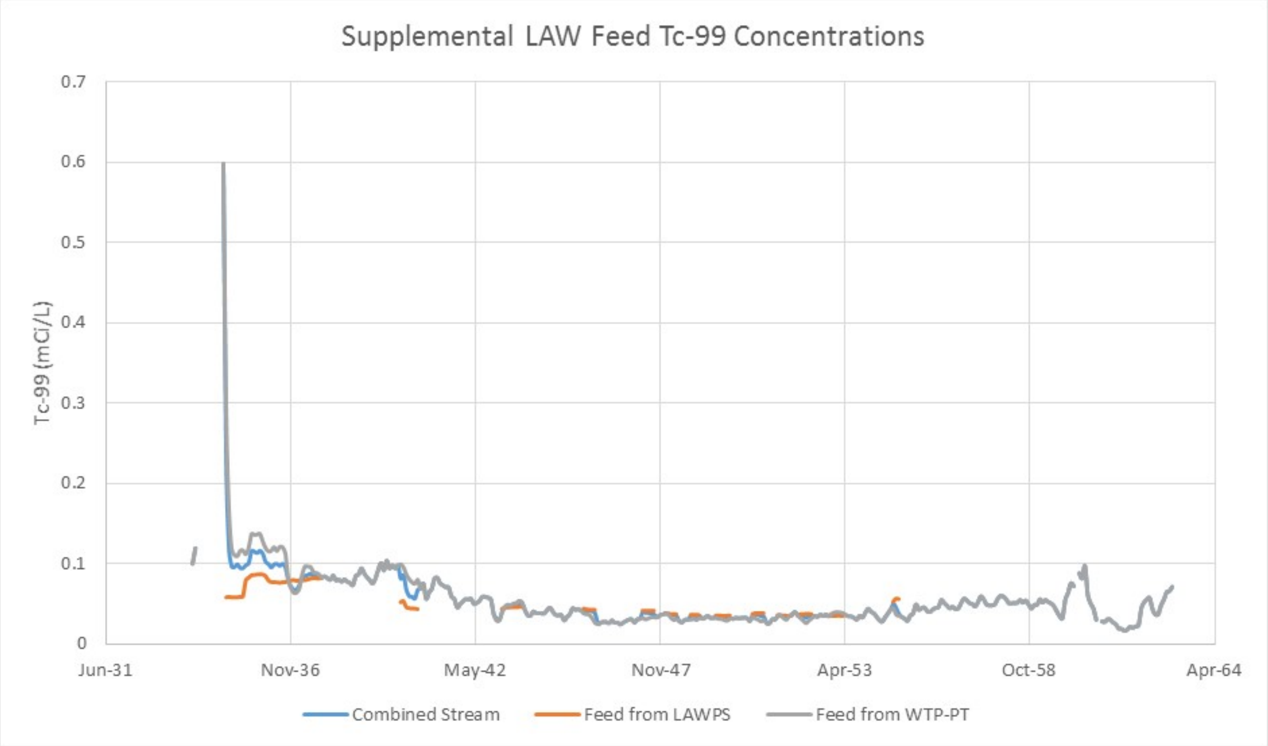


Figure J-6. Tc-99 Concentrations

In addition, as a result of the unconstrained model and the desire to achieve full capacity through the HLW vitrification facility, the SLAW will also need to accommodate extremes in feed volume, as shown in Figure J-7. The use of the feed vector to determine the required size of the immobilization facility for cost estimation will provide a consistent capacity target for each immobilization technology. The cost estimate comparisons are expected to be scalable such that the differences noted in costs would be expected to be similar if a different capacity is chosen for SLAW.

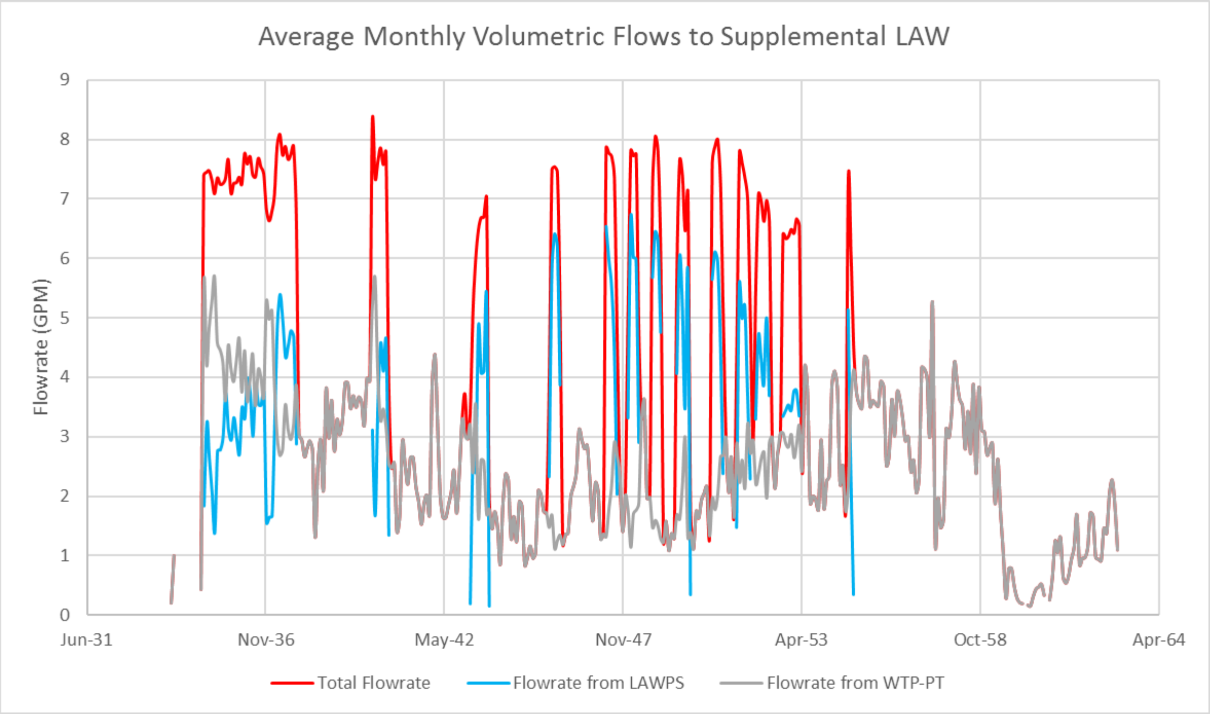


Figure J-7. SLAW Feed Volumes

J.2.3.3 Integrated Flowsheet

The One System Integrated Flowsheet was utilized as the source for the SLAW feed vector used in the evaluations of different immobilization technologies. The Integrated Flowsheet is a material balance surrounding the entire tank waste immobilization program at Hanford and is updated approximately every two years. It is the only source identified that calculates the feed vector for SLAW from up to date information that includes the impact of recent decisions on how the tank waste will be processed (such as the inclusion of direct feed options). The flowsheet calculations were performed using a TOPSim model as described in the model requirements document[10] which lists the calculational techniques and assumptions made in the calculations for each unit operation.

The TOPSim model has a number of simplifications that allow the entire Hanford waste disposition flowsheet to be modeled in a timely manner. These simplifications include, but are not limited to:

- single parameter “split factors” to determine partitioning of most species through each unit operation including the melter and melter offgas system
- lack of inclusion of the impact of melter idling on emissions from the melter
- SLAW modeled as a “black box”
- Flushes of transfer lines in the WTP are not modeled

The use of single factor split factors and the lack of impacts from idling impact the recycle streams from the HLW and LAW melter offgas systems and could lead to non-conservative assumptions of semi-volatile species (^{129}I, ^{99}Tc, S, Cl, F, e.g.) in the feed to SLAW[11]. The single parameter split factors do not account for any process variation from changing feed compositions, but it is not possible to determine if the impact of this simplification

would be conservative or non-conservative. The lack of flush water additions in WTP in the model primarily reduces the estimated amounts of secondary waste generated from LAW and SLAW processing, but additional impacts could occur if the diluted feed results in different partitioning than assumed.
It should also be noted that the retrieval sequence and processing assumptions (direct feed option timing and processing amount, e.g.) impact the amount of feed processed through SLAW as well as the composition. As with the split factor assumptions, it is not possible to state whether the current estimates are conservative or non-conservative.

An additional consideration for using the feed vector is that it could be possible to generate an integrated flowsheet that performs acceptably with some constraints placed on SLAW feeds to prevent the most extreme conditions noted in the current feed vector. Thus, a proposed flowsheet should not be automatically eliminated from consideration if a small set of conditions noted in the current vector are outside the ranges possible with the flowsheet.

Finally, it is noted that the Sm-151 concentrations in the feed vector are much higher than comparable streams at the SRS. The Sm-151 concentration of feed to Saltstone is typically less than detectable, indicating that Sm-151 is very insoluble in SRS wastes. Thus, the Sm-151 concentrations in the SLAW feed vector should be considered very bounding.

J.3 FLYWHEELS AND IMPACT ON SLAW

J.3.1 Flywheel Description

The single pass retention of selected species (such as Tc) is less than 50% during the LAW vitrification process due to the high temperature of the melter leading to a portion of these species vaporizing from the melter. The majority of these species are efficiently captured in the condensate from melter offgas such that losses to the stack are minimal. In order to increase the overall retention of Tc, the melter offgas condensate is evaporated to remove water, then recycled to the melter feed. The recycle loop increases the Tc retention, but also recycles species such as Cl, F, and S which can decrease the allowable waste loading the glass. Recycling material in this manner increases the concentrations of the species recycling in the recycle “flywheel” until the single pass retention is high enough to purge the species from the flywheel at the same rate as the incoming feed adds the species to the flywheel. This process is shown Figure Lx for a species with a 33% single pass retention in a simplified flywheel with no losses to the offgas systems.

Note that the melter feed amount has increased from 1 kg/day in the feed to 3 kg/day in the flywheel to allow a 33% retention to remove 1 kg/day in the glass. If the single pass retention was lower, then the concentration in the flywheel would increase. Thus, if single pass retention was 10%, then the amount in the recycle would increase to 9 kg/day and the amount in the melter feed would increase to 10 kg/day.

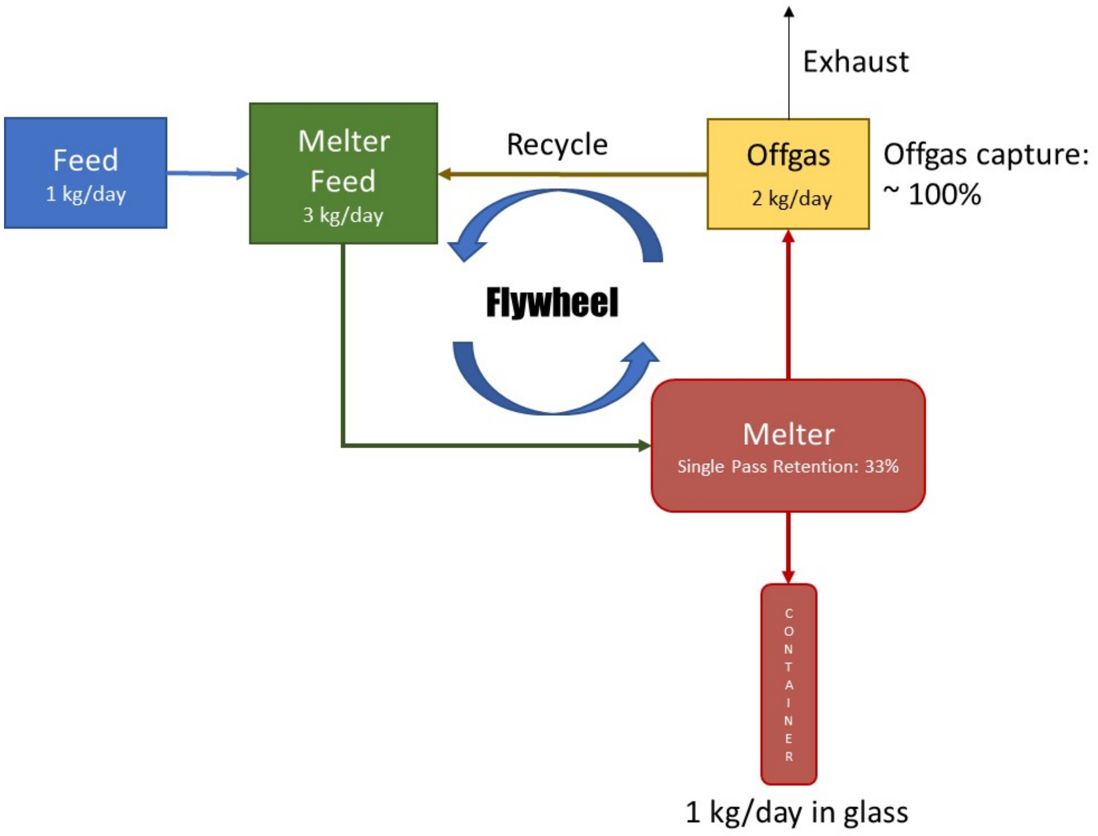


Figure J-8. Simplified Flywheel.

The flywheel in the LAW system after startup of SLAW is more complicated, as is shown in Figure J-9. Note that Cl, Cr, F, Hg, I, S, and Tc are the primary species that will flywheel in the system. Note that water is also part of the flywheel, requiring the evaporation step in the EMF to purge water. Since the SLAW feed represents an additional purge point, the overall concentration in the flywheel is decreased. In this example, approximately 50% of the melter feed is sent to SLAW, this ratio will change during operation and impact the distributions in the flywheel.

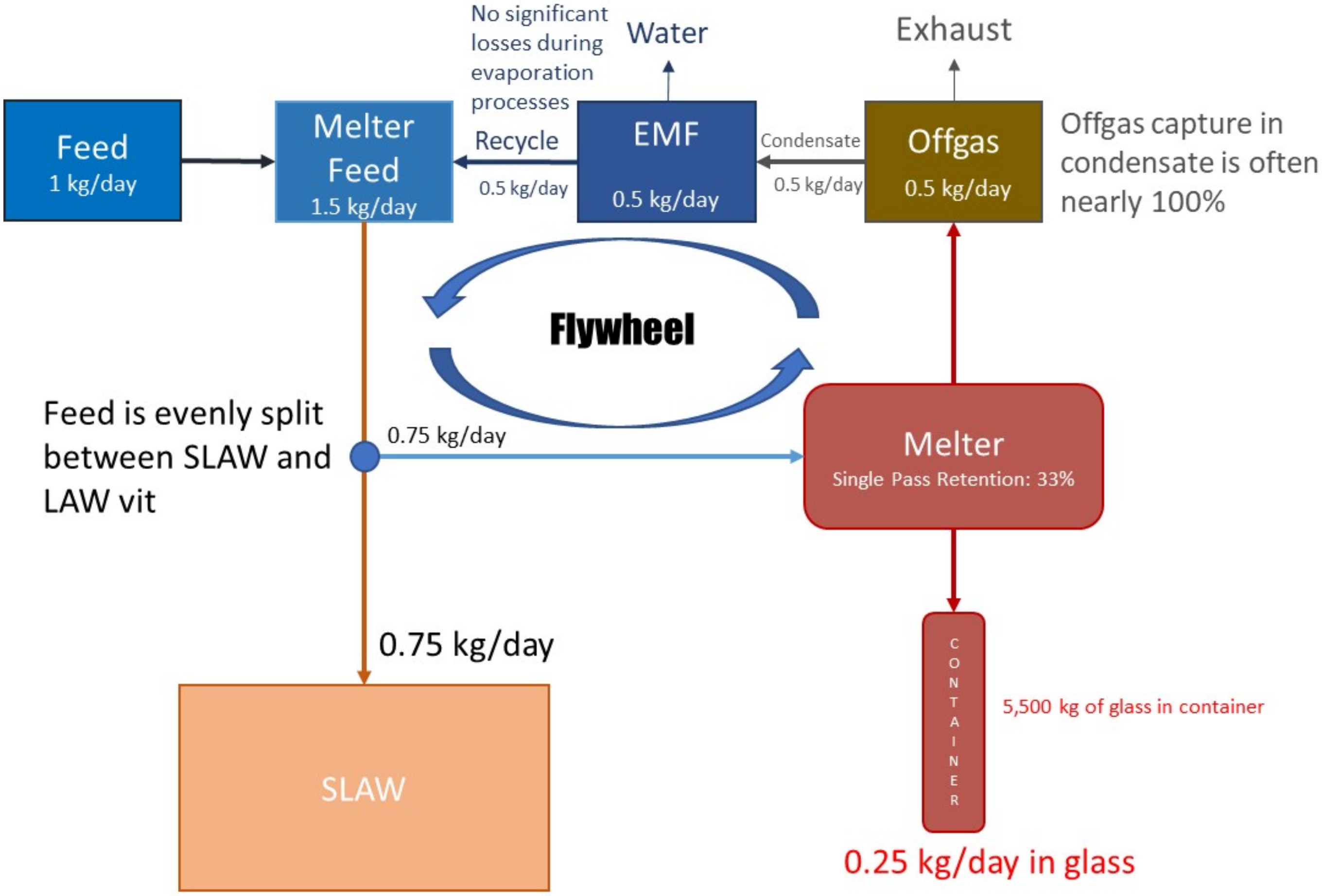


Figure J-9. LAW Flywheel

J.3.2 Impact on SLAW

The recycle flywheel could have two impacts on SLAW. First, the amount of LAW glass required to immobilize the treated LAW supernate could increase if waste loading is decreased from the higher amounts of Cl, F, and S if the single pass retention of these species is lower than assumed in the model. Since the LAW facility is at capacity throughout the WTP mission, then increase in capacity for LAW treatment must occur at the SLAW facility. Therefore, the flywheel could impact the amount of material sent to SLAW.

Second, the composition of the feed to SLAW is impacted if the single pass retention in the LAW flywheel changes. As shown in Figure J-9, 75% of the semi-volatile species is sent to SLAW even though the feed volume is evenly split in the example. If the single pass retention of a species is lower, then a greater percentage of the species is immobilized at SLAW versus the LAW facility. If the single pass retention is 10% for LAW, then approximately 91% of the species will eventually be sent to SLAW even if the melter feed stream flow continues to be split evenly between LAW and SLAW.

Melter idling leads to decreased single pass retention of species since the vaporization of these species from the melt increases during idling, depleting the melt pool and increasing the amounts sent to the offgas. Melter idling is not modelled during the Integrated Flowsheet; therefore, it can be assumed that the overall single pass retention of Tc will be less than assumed in the model. For comparison to the figures above, the single pass retention of Tc is assumed to be 38% in the Integrate Flowsheet models based on an average of pilot plant retention data.

In addition, if vitrification is chosen as the wasteform for SLAW, a similar recycle loop will be required in the SLAW facility to ensure that the Tc is incorporated into the glass product. It can be assumed that similar issues that could reduce the single pass retention in the LAW facility could also impact the SLAW flywheel.

J.4 SLAW FEED VECTOR UNCERTAINTIES

J.4.1 Volume to be Processed Through SLAW

In addition to the potential differences in the feed vector, evaluations are in progress that could change the way Hanford tank waste is processed. Rather than list each of the possible changes, it should be assumed that many aspects of tank waste retrieval and immobilization could change from the current assumptions. These changes have the potential to minimize the need for a single SLAW facility tied directly to the WTP facility as assumed in this evaluation and could potentially include smaller, modular systems designed to treat the waste at the individual tank farms or even individual tanks within a farm.

It was assumed that the throughput through the current WTP LAW is not likely to change dramatically as the models used in the Integrated Flowsheet contain most of the expected improvement in waste loading. The model assumes 70% attainment and operation at nameplate capacity, two conditions that the WTP LAW facility is not likely to exceed. Thus, the throughput through the WTP LAW facility should not be expected to be higher than assumed in the flowsheet and the amount of feed to SLAW will not decrease if the LAW mission schedule is not changed.

Changes in the required throughput of SLAW could occur if the schedule for completion of LAW immobilization changes from the current assumptions. It is noted that acceleration of the mission is not simply a matter of building a larger scale immobilization facility; tank farm operations would need to be scaled similarly to allow retrieval of waste to meet the processing needs of the larger facility.

Finally, it was assumed that all wastes in the tank farms (except that classified as TRU waste in the Integrated Flowsheet) would be retrieved and immobilized. Some initiatives are underway to evaluate re-classification of portions of the tank waste, but these changes were not considered during this review.

Therefore, the facilities for each immobilization technology will be sized as needed to process the feed vector as specified in the Integrated Flowsheet. Regarding project costs, the results from this evaluation should be scalable such that the results can be used to evaluate the technology for supplemental immobilization of LAW. Thus, it is assumed that the evaluation performed based on a single SLAW facility could be applied to smaller modular systems. It is noted that smaller, modular systems could allow the waste treatment to be tied to the specific needs of individual tank farms or tanks, which may allow consideration of treatment options that would not be appropriate for all of the waste to be treated in the current assumptions for SLAW treatment.

J.4.2 Challenges with Using System Plan 8

A number of programmatic challenges, outside the scope of this review of SLAW, could impact the feed vector (both composition and volume). As stated above, the best estimate for the material to be processed through the SLAW facility is the current revision of the Integrated Flowsheet. This flowsheet is based on assumptions contained in System Plan 8[126]. It is noted that System Plan 8 contains a number of different processing scenarios,

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[126] “River Protection Project System Plan,” U.S. Department of Energy: Office of River Protection, Richland, Washington,

the Integrated Flowsheet is based on the baseline scenario. A number of the assumptions in the System Plan impact the feed composition and size requirements for SLAW. The most significant of these assumptions are the funding levels needed to perform the mission as described in the System Plan, the retrieval rates of waste from tank farms, and the ongoing resolution of technical issues related to restarting the construction of the WTP PT and HLW facilities. BNI has submitted the proposed resolutions to DOE-ORP, but final approval that the technical issues are resolved has not been obtained. Restart of the construction of these facilities is assumed in System Plan 8; delays in obtaining approval would delay the start of these facilities past the dates assumed.

The funding assumptions in the System Plan assume that funding is increased (unconstrained) whenever needed to perform capital projects to construct or upgrade facilities while operating existing facilities. The annual funding needed to support this assumption represents funding increases that could be double or triple the current annual expenditures. If the funding profile remains flat, then the required facilities to perform System Plan 8 will not be available when required. Thus, the mission need for SLAW could change depending on the actual funding levels provided.

The retrieval rates assumed in System Plan 8 will require upgrades to the tank farm facilities and a change in operational paradigm to achieve. The single shell tanks at Hanford were operationally isolated from other tanks by cutting and sealing transfer lines in and out of the tanks and the infrastructure that supported transfers was not maintained. Retrieval of waste from "C" farm has been completed, but challenges were identified, e.g. tank vapors, that slowed work. Resolution of these issues as well as the completion of the required upgrades is assumed in System Plan 8. In addition, System Plan 8 assumes retrieval and transfer efficiencies/improvements that have not yet been demonstrated by tank farm operations. The number of transfers needed to be performed in a year will need to increase by orders of magnitude to support WTP operation; the ability to accelerate processing to the levels assumed in System Plan 8 is not certain.[127]

J.5 CONCLUSIONS

The feed vector provided by WRPS is the best information available and has been used to perform the assessment of proposed flowsheets for SLAW disposition. The capacity of the SLAW facility should be based on the flowrates to SLAW in the feed vector.

It is noted that the TOPSim model used contains simplifications that may result in non-conservative values for selected species. In addition, some of the peaks in the data may be avoidable by a different retrieval/staging strategy than utilized in the case prepared for the Integrated Flowsheet. In addition, treatment of individual tanks with at-tank treatment could also generate treated LAW that is not bounded by the feed vector.

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Acronyms

REDOX	REDuction and OXidation
PUREX	Plutonium Uranium Extraction
WTP	Hanford Waste Treatment and Immobilization Plant
PT	PreTreatment Facility
LAW	Low Activity Waste
HLW	High Level Waste
LERF/ETF	Liquid Effluent Retention Facility / Effluent Treatment Facility
LAWPS	Low Activity Waste Pretreatment Facility
IDF	Integrated Disposal Facility
LDR	Land Disposal Restrictions

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