

FFRDC Team Working Draft Documents – 2017 NDAA 3134 Hanford Supplemental Low Activity Waste Treatment at the Hanford Reservation

The following attached document has been developed by the FFRDC Team and represents a “working draft” report regarding assessment methodologies, technologies, and approaches under consideration and review per the FFRDC Program Plan developed for this study.

The FFRDC Team recognizes that under the NDAA 3134 language, the collaboration with the NAS is critical to achieving the intended goal of the study. As such, working draft information is being shared.

It is important for readers to understand that much of what is presented in these working draft documents has not been peer reviewed and is not intended to imply any final conclusions or represent a complete analysis. Peer reviews and subsequent revision and refinement will be completed during the spring of 2019. Until a final report is formally issued, all information presented is considered Pre-Decisional DRAFT.

The intent of sharing the working draft report is to stimulate dialog with the NAS Committee members and to ultimately obtain constructive feedback comments to improve the report. This draft report will provide an opportunity for the Committee to review it prior to the pending public meeting tentatively scheduled for 1/8/19.

Bill Bates

FFRDC Team Lead

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



Pacific Northwest
NATIONAL LABORATORY



PRELIMINARY DRAFT

2018-12-21 DRAFT

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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

DOE	Department of Energy
EM	DOE Office of Environmental Management
EMNLN	EM National Laboratory Network
ETF	Effluent Treatment Facility
FFRDC	Federally Funded Research and Development Center
GAO	Government Accounting Office
IDF	Integrated Disposal Facility
INL	Idaho National Laboratory
HLW	high level waste
LANL	Los Alamos National Laboratory
LAW	low-activity waste
LAWPS	Low Activity Waste Pretreatment Facility
LDR	Land Disposal Restrictions
LERF	Liquid Effluent Retention Facility
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
POC	point of contact
PNNL	Pacific Northwest National Laboratory
PT	Pretreatment Facility
PUREX	Plutonium Uranium Extraction
REDOX	REDuction and OXidation
SRNL	Savannah River National Laboratory
TOC	Tank Operations Contract
WCS	Waste Control Specialists
WTP	Waste Treatment and Immobilization Plant

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To be added to final report.

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EXECUTIVE SUMMARY

This report describes the results of the analysis of alternatives for supplemental treatment of low-activity waste (LAW) at the Department of Energy's (DOE's) Hanford Nuclear Reservation prescribed by the National Defense Authorization Act for Fiscal Year 2017 (NDAA17).

The report concludes that a viable process flowsheet and disposal option can be developed for each of the three technologies evaluated (vitrification, grout, and steam reforming) without requiring removal of technetium or iodine. On-site disposal options for grout and steam reforming would reduce the cost of these options, but these options remain more economical than vitrification even if off-site disposal is utilized. Grout was determined to be the lowest cost option.

BACKGROUND AND MISSION

The current design of the Waste Treatment and Immobilization Plant (WTP) at the Hanford site enables treatment of only a portion of Hanford's LAW. To increase Hanford LAW treatment capacity, construction of an additional facility for treating the remainder of the LAW has been proposed.

NDAA17 Section 3134, "Analysis of Approaches for Supplemental Treatment of Low-Activity Waste at Hanford Nuclear Reservation," stipulates that a Federally Funded Research and Development Center (FFRDC) team conduct an analysis of approaches to treating the portion of LAW at the Hanford site that is intended for supplemental treatment. FFRDCs, such as 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.

The DOE Office of Environmental Management (EM) directed the Savannah River National Laboratory to lead the team. The FFRDC core team was constituted through the EM National Laboratory Network, which recommended experts from six national laboratories who are accomplished in disciplines pertinent to key aspects of the analysis. The six national laboratories are Savannah River, Pacific Northwest, Los Alamos, Idaho, Sandia, and Oak Ridge.

NDAA17 also directs the National Academies of Science, Engineering, and Medicine (NAS) to conduct a review of the supplemental LAW (SLAW) analysis concurrent with the FFRDC team's analysis. The FFRDC team interfaces formally with the NAS Committee through public meetings and through the reports issued by the NAS committee providing comments and recommendations to the FFRDC team. In addition to the public meetings, several members of the NAS Committee also attended and observed two FFRDC team working meetings in May 2018 in Aiken, SC and October 2018 in Albuquerque, NM.

APPROACH TO ANALYSIS

The FFRDC team analyzed several approaches to treatment of Hanford SLAW--vitrification, grouting, steam reforming, and "other" potential methods—as well as pretreatment requirements for those approaches. The team also analyzed disposal of the immobilized wastes on-site and at an off-site commercial disposal facility.

Cases for Analysis

The FFRDC team developed 22 process cases ("flowsheets"). The team also developed flowsheets for pretreatment scenarios to remove selected radionuclides and other problematic constituents.

In May 2018, the full team used the Analytical Hierarchy Process (AHP) to evaluate the relative strengths and weaknesses of those 22 cases. That evaluation condensed the 22 cases to 12 cases for further development.

In preparation for the Risk Analysis meeting in October 2018, the team selected the best representative cases for the three technologies specified in the NDAA17, specifically one for Vitrification and two each for Grout and Steam Reforming to accommodate both on-site and off-site disposal options. Table 1 below distinguishes the five cases regarding pretreatment, primary waste disposal, and secondary waste disposal*:

Table 1-Five best representative cases for SLAW processing technologies specified in the NDAA17

Option	Pretreatment	Primary Waste Disposal Facility	Secondary Waste Disposal Facility
Vitrification	None	IDF	IDF
Grout Case 1	LDR	IDF	IDF
Grout Case 2	LDR	WCS	IDF
Steam Reforming Case 1	None	IDF	IDF
Steam Reforming Case 2	None	WCS	WCS

*Key

LDR: Resource Conservation and Recovery Act (RCRA) Land Disposal Restrictions

IDF: on-site Integrated Disposal Facility, Hanford

WCS: off-site Waste Control Specialists, Texas

Performance Evaluation and Risk Analysis

The team performed two types of analyses, analysis of programmatic risks and evaluation of long-term performance of the waste in the on-site IDF. The Performance Evaluation of the IDF used software and input parameters and timeframes similar to those used for the formal Performance Assessment (PA) of the IDF to analyze the ability of grout and steam reformed waste forms to meet the same performance criteria. The semi-quantitative Risk Analysis performed in October 2018 assessed the project and programmatic risks for all 5 cases identified above. This effort also included cross-cutting system-level risks applicable to all 5 cases that may be outside the control of the project and program to manage (e.g., sufficient Congressional appropriations).

Comparative Analysis

Table 2 below presents a high-level comparison of the three technologies specified in the NDAA17 in regard to the attributes specified in NDAA17. Schedule durations reflect the number of years needed before facility hot start-up. Costs are full life-cycle costs, which include project construction, operations, transport, and deactivation and decommissioning. A more detailed table is included in Appendix L. Note that the columns for grout and steam reforming encompass both on-site and offsite disposal options, so only 3 columns are used in this table to describe the 5 cases evaluated.

Table 2-High-level comparison of the three technologies specified in the NDAA17 in regard to the attributes specified in NDAA17

NDA PARAMETERS	VITRIFICATION	GROUT	STEAM REFORMING
COST	\$19B-\$40B	\$2B-\$10B	\$8B-19B
SCHEDULE	10-21 Years	8-13 Years	10-15 Years
BENEFITS	• Current baseline • Most technically mature for SLAW feed • Thermal LDR organic/nitrate destruction • Lowest primary waste volume	• Lowest temperature process (less offgas, stop/start flexibility, safety) • Least complex process • Utilizes vast international experience • Lowest secondary waste volume	• Lowest cost thermal LDR organic/ nitrate destruction • Medium primary & secondary waste volume
REGULATORY COMPLIANCE	• Primary waste form compliant for onsite disposal (IDF) • Secondary grout waste form & onsite disposal (IDF) pending	• High likelihood to meet DOE Technical Performance Criteria for onsite disposal (IDF) • Secondary solid waste form & onsite disposal (IDF) pending	• High likelihood to meet DOE Technical Performance Criteria for onsite disposal (IDF) • Secondary solid waste form & onsite disposal (IDF) pending
	All waste forms are compliant with offsite transport and disposal (WCS).		
RISKS/ OBSTACLES (Technical)	• Most dependent on integrated facility performance (DFLAW, WTP, TF) ○ Most complex ○ Highest throughput risk ○ Most impacted by feed rate variability • Highest secondary waste volume (liquid and solid)	• May require System Plan feed adjustments or pretreatment to address organic species (Tc/I) • Highest primary waste volume • Additional validation/demonstration of waste form performance needed	• Lowest technical maturity • Latest waste form performance tests show promise, but more needed for regulator/stakeholder acceptance
RISKS/ OBSTACLES (Programmatic)		• Potential lack of stakeholder/regulator acceptance for onsite disposal (IDF)	• Potential lack of stakeholder/regulator acceptance for onsite disposal (IDF)
	All technologies require significant concurrent Line Item and operations funding (> \$1.5B/yr).		

MAJOR PROGRAMMATIC CHALLENGES

The program to disposition the Hanford tank waste is technically complex, with many interdependencies among processes. For example, a change in the rate of WTP high level waste (HLW) processing would have a direct impact on the Supplemental LAW (SLAW) feed rate. Many other examples of complexity and interdependency

exist. The following discussion describes some of the major programmatic challenges that make SLAW technology analysis and selection difficult.

Program and Project Cost Estimates

While cost and schedule estimates were developed for the 5 cases, it must be recognized that these are budget planning estimates and are very preliminary based on a comparison to other projects from the DOE Complex. These estimates include all aspects of the program from research and development (R&D) through capital project development, operational life cycle, and dismantlement. While the individual estimates are not at a high level of maturity (mature estimates typically occur after capital project design is completed), cost range estimates are provided here to allow decision-makers to compare different alternatives and any overlap in ranges.

Schedule Urgency

To enable SLAW processing to complete concurrently with HLW processing, hot startup of the SLAW processing facility is assumed to be needed by 2034. Assuming several years will be needed for Congress to authorize a capital Line Item project, this allows less than 15 years to complete R&D and to build and startup an immobilization facility.

Supplemental LAW Feed Uncertainties

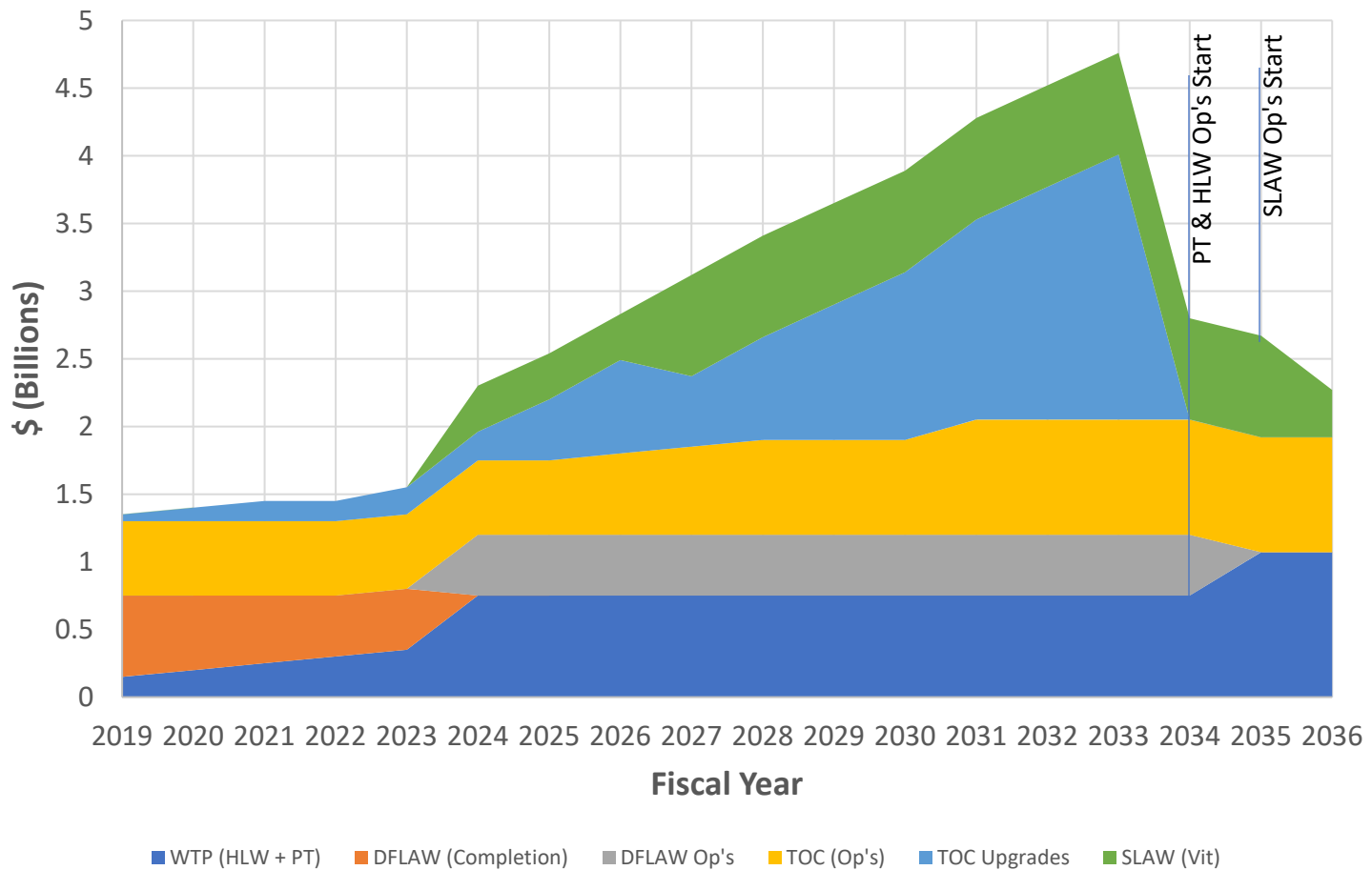
SLAW contents and volumes are based on Hanford Office of River Protection System Plan Revision 8¹. This plan uses models based on best available data from the history of waste tank contents to calculate the anticipated feed flows as well as the radionuclides and other constituents that must be treated to comply with Resource Conservation and Recovery Act (RCRA) Land Disposal Restrictions (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, as mentioned above, variability in tank waste removal and WTP pretreatment and HLW processing rates can impact throughput and SLAW pretreatment processing demands.

Significant Funding Needs

To build the new SLAW process, significant annual funding will be needed. Between now and 2034, the construction of WTP will continue, and operational costs for the Direct Feed LAW (DFLAW) process will be starting. Regardless of the technology selected for SLAW, it is expected that more than \$1.5B will be required annually to keep each of the major waste processing programs progressing on the current schedule. This appears to be a significant risk to overall integrated program success. There is a risk applicable to any selected SLAW processing technology that lack of funding appropriations could extend overall waste tank storage durations, thus extending and increasing tank storage risk. The following schematic shows this "stacked cost" challenge graphically. It should be noted that the SLAW 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.

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

WTP and Tank Operations Contract (TOC) Budget Forecast



Notes:

1. Facility Operations (rad-op's) start dates assumed to match System Plan 8 Baseline Case as per basis for this study.
2. Assumes ongoing WTP projects (HLW, PT and DFLAW) are flat funded at \$750M per year, implying combined HLW/PT to go costs equate to \$9.5B. These values are not verified and are for reference only.
3. TOC estimates are interpolated from System Plan 8, Baseline Case, except Supplemental LAW.
4. Supplemental LAW Vitrification is reflected at the lower end for Total Project Cost and annual operations per this study. Flat funding ceiling of \$750M annual assumed for SLAW project.
5. Costs are not escalated.
6. Schedule requirements mandate significant increase ($\approx$ \$750M) starting in or around 2024 and annual increases of $\approx$ \$250M through 2033.

Stakeholder and Regulator Acceptance of On-site Disposal of non-glass Waste Form

It is a realistic possibility that even if non-vitrified waste forms are shown through a formal PA to meet DOE performance criteria for disposal at the IDF, regulators may still reject a non-glass waste form. Some stakeholders hold a strong bias to glass waste forms above any others consistent with the "good as glass" phrase frequently used by those stakeholders. This consideration is significant if on-site disposal is considered.

Secondary Waste Disposal

Secondary wastes include solid waste such as air filters as well as liquid wastes generated during processing of primary waste forms. The current System Plan 8 assumption is that all solid secondary waste will be disposed of as a grouted waste form, while liquid secondary waste will be sent to the Liquid Effluent Retention Facility-Effluent Treatment Facility (LERF-ETF). Solids removed during treatment of the liquid effluents at LERF-ETF also are assumed to be grouted. The disposition of secondary waste for vitrification options has been analyzed in the PA, but the permit has not yet been approved. There is some risk that secondary waste could also be a challenge for regulators. This could lead to considerations of other waste forms or disposal options for secondary wastes from the SLAW process and could also impact WTP LAW secondary waste.

Future Scenarios

Over the years, numerous alternative concepts to 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 models or process models
- Use and acceptance of waste form performance tests for non-glass waste forms.

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

COMPARISON TO THE ENVIRONMENTAL IMPACT STATEMENT

The most recent Environmental Impact Statement (EIS)² concludes that the cost of grouting and steam reforming would be similar to the cost of vitrification but that the grouted and steam-reformed waste forms would not comply with performance criteria for IDF disposal. This FFRDC study has drawn different conclusions related to cost and performance. Table 3 below provides some key differences between the EIS and the current study:

Table 3 to be developed based on EIS cost comparison and performance evaluation.

SUMMARY

The report and appendices that follow provide greater technical details on the key topics introduced above. This report is not intended to provide a recommendation regarding technology selection but does provide an objective comparative analysis of the primary cases that apply the specific technologies and waste disposal options specified in NDAA17 3134 with regard to the six NDAA17 3134 parameters (shown in Table 2 above).

The study has concluded that vitrification, grouting, and steam reforming can meet DOE performance criteria that can support development of a formal Performance Assessment (PA) for Hanford IDF disposal. Additionally, the study concludes that off-site disposal at WCS is also technically viable.

² "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.

1.0 PARAMETERS OF THE ANALYSIS

1.1 STRATEGY

As summarized in Appendix A, the “Best Practices for the Analysis of Alternatives” established by the United States Government Accountability Office (GAO)³ was used to provide general guidelines for the analysis of alternatives for supplemental treatment of low-activity waste (LAW) at the Department of Energy’s (DOE’s) Hanford Nuclear Reservation.

1.1.1 Need and Requirements

The current design of the Waste Treatment and Immobilization Plant (WTP) at DOE’s Hanford site in Richland, Washington enables treatment of only a portion of Hanford’s low-activity waste (LAW). To increase Hanford LAW treatment capacity, construction of an additional facility for treating the remainder of the LAW has been proposed.

Section 3134, “Analysis of Approaches for Supplemental Treatment of Low-Activity Waste at Hanford Nuclear Reservation,” 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 to treating the portion of LAW at the Hanford site that is intended for supplemental treatment at the time of the enactment.⁴ FFRDCs, such as 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.⁵

NDAA17 Section 3134 also directs the National Academies of Science, Engineering, and Medicine to conduct a review of the LAW analysis concurrent with FFRDC performance of that analysis.

1.1.2 Methodology

SRNL was asked by DOE-EM to lead the analysis. SRNL constituted the FFRDC team through the Environmental Management National Laboratory Network (EMNLN). The EMNLN facilitates the ability of the DOE Office of Environmental Management (EM) to access and leverage the capabilities of the DOE national laboratories to meet the objectives of EM’s legacy nuclear waste clean-up mission.⁶ Representing six national laboratories, the members of the core FFRDC team are expert and accomplished in disciplines pertinent to key aspects of the analysis and are readily able to “reach back” to utilize the broader experience, expertise, and capabilities of their own laboratories as well as to “reach out” to colleagues in other National Laboratories, industry, and academia for support as needed. The team developed a Program Plan to guide performance of the analysis.⁷

As prescribed in the NDAA17, the FFRDC team analyzed several approaches to immobilization of Hanford LAW--vitrification, grouting, steam reforming, and “other” potential methods—as well as pretreatment requirements for those methods. The analysis included the following major elements:

³ DOE AND NNSA Project Management: Analysis of Alternatives Could Be Improved by Incorporating Best Practices. GAO-15-37. December 2014. Report to the Committee on Armed Services, U.S. Senate. United States Government Accountability Office.

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

⁵ “Federally Funded Research and Development Centers.” 48 CFR 35.017. October 1, 2005. United States Code of Federal Regulations.

⁶ “EM National Laboratory Network Charter.” May 2017.

⁷ “Program Plan for Analysis of Approaches for Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation.” SRNL-RP-2017-00242. June 2017.

- Development of pre-conceptual flow sheets
- Development of variants and opportunities
- Development of criteria for analysis and comparison of options
- Review of regulatory requirements for processing, transport, and disposal
- Identification and evaluation of potential risks associated with the options
- Development of pre-conceptual cost estimates
- Performance of an Expert Elicitation review and comparison of all options against the established criteria.

The team applied a broad set of variously weighted technical, regulatory, cost, maturity, and other criteria to evaluate each of the 3 original base cases as well as 9 variants identified by the team and then performed comparisons among the options, eventually selecting the five best representative cases for the three technologies specified in the NDAA17, specifically one for Vitrification and two each for Grout and Steam Reforming to accommodate both on-site and off-site disposal options.

Appendix I, “Expanded Discussion: Comparative Analysis Of Approaches,” provides the criteria, weight factor, and comparison of the options.

1.2 SCOPE

Section 3134 of NDAA17 specifies that an FFRDC team conduct an analysis of approaches to treating the portion of LAW at the Hanford site that is intended for supplemental treatment at the time of the enactment.

The only identified documentation specifying the feed stream intended to be processed through the future Supplemental LAW process is the One System River Protection Project Integrated Flowsheet. At the time of the enactment of the Act, revision 1 of the Integrated Flowsheet was issued⁸; Revision 2 was still in draft. Revision 2 was issued in September 2017 based on processing assumptions in System Plan 8⁹ and utilizes updated glass modeling to reduce the size of the Supplemental LAW facility required. The models utilized during Revision 2 also allow extraction of a monthly feed vector to Supplemental LAW, while Revision 1 could be utilized only to provide an overall mission average. Older documents contain feed vectors for LAW^{10,11}, but these documents contain assumptions about LAW processing that are no longer valid.

In order to provide a common basis for evaluation of the immobilization technologies with enough fidelity to perform the evaluation, the feed to Supplemental LAW was assumed to be the Supplemental LAW feed vector from Revision 2 of the Integrated Flowsheet¹². The initial evaluation of each flowsheet will utilize the Supplemental LAW feed vector with no modifications, and additional pretreatment will be evaluated as needed.

⁸S.T. Arm, R.D. Claghorn, J.M. Colby, L.H. Cree, M.F. Fountain, D.W. Nelson, V.C. Nguyen, R.M. Russel, and M.E. Stone, “One System River Protection Project Integrated Flowsheet, RPP-RPT-57991, Rev. 1,” Office of River Protection One System, Richland, WA, 2015.

⁹“River Protection Project System Plan.” ORP-11242. Rev 8. 2017. U.S. Department of Energy Office of River Protection. Richland, Washington.

¹⁰D.J. Swanberg, A.D. Cozzi, W.E. Daniel, R.E. Eibling, E.K. Hansen, M.M. Reigel, J. Westik, J.H., G.F. Piepel, M.J. Lindberg, P.G. Heasler, T.M. Mercier, and R.L. Russell, “Supplemental Immobilization of Hanford Low-Activity Waste: Cast Stone Screening Tests,” Washington River Protection Solutions, LLC., Richland, Washington, RPP-RPT-55960, Revision 0, 2013.

¹¹J.R. Baker, “Supplemental Treatment Project Immobilization System Feed Composition - Revision 0,” AEM Consulting, Richland, Washington, SVF-2007, 2010.

¹²L.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.

Pretreatment was evaluated separately from the immobilization technology unless shown to be needed to make the immobilization technology viable.

1.3 UNCERTAINTIES

The four major areas of uncertainty identified as impacting the evaluation of immobilization technology for Supplemental LAW are described in sections 1.3.1-1.3.4 below.

1.3.1 Feed Vector Composition

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 previously¹³ as well as the impacts of a 20% variation for selected components on the baseline process¹⁴. The evaluation of uncertainty determined that 20% is not a bounding value for the BBI uncertainty, 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 grout process. Selected RCRA metals, such as silver and barium, are considered supplemental analytes and data is available for only some of the wastes.

Second, the feed vector provided from the Integrated Flowsheet is based on proposed processing for retrievals and facility startup times that may change prior to Supplemental LAW 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 sequence¹⁵.

Third, the TOPSim model used to generate the feed vector has many simplifications¹⁶. 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
- Supplemental LAW modeled as a “black box”
- Lack of modeling flushes of transfer lines in the WTP are not modeled.

The use of single factor split factors and the lack of impacts from idling affect the recycle streams from the HLW and LAW melter offgas systems and could lead to non-conservative assumptions of semi-volatile species (e.g., ¹²⁹I, ⁹⁹Tc, S, Cl, F) in the feed to Supplemental LAW¹⁷. The single parameter split factors do not account for any process variation from changing feed compositions, but it is unknown whether 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 WTP LAW and Supplemental LAW processing, but additional impacts could occur if the diluted feed results in different partitioning than assumed.

¹³ 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.

¹⁴ 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.

¹⁵ 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.

¹⁶ 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.

¹⁷ R.F. Gimpel, “DFLAW Sensitivity Studies for Melter Idling Impacts, 24590-WTP-MRR-PENG-16-004, Rev 0,” Bechtel National Incorporated, River Protection Project Waste Treatment Plant, Richland, WA, 2016.

It should also be noted that the prediction of the concentration of soluble strontium and other species is often not within a factor of 2 of the actual concentration using the solubility models in TOPSim¹⁸. Thus, the uncertainty in the concentration data in the feed vector further compounds the uncertainty in the BBI source data.

Thus, uncertainty in the compositions to be processed exist 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 will provide an understanding of how components impact the immobilization technology. If a tank is retrieved and determined to be significantly outside the ranges evaluated, it is assumed that blending with other tank waste could mitigate the issue if the feed is determined to be out of the processing range for the chosen technology.

1.3.2 Supplemental LAW Mission: Volume to be Processed Through Supplemental LAW

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 Supplemental LAW 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 Supplemental LAW will not decrease if the LAW mission schedule is not changed.

Changes in the required throughput of Supplemental LAW could occur if the schedule for completion of LAW immobilization changes from the current assumption of 40 years after the start of HLW process (to allow the LAW mission end to coincide with HLW mission end)¹⁹. 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 are 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.

¹⁸ Pierson, K. L. "Evaluation of the HTWOS Integrated Solubility Model Predictions." RPP-RPT-53089. 2012. Washington River Protection Solutions. Richland, Washington.

¹⁹ 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.

Thus, it is assumed that the evaluation performed based on a single Supplemental LAW 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 Supplemental LAW treatment.

It is likely that a decrease in mission scale or duration would make capital cost intensive technologies less cost competitive while a technology that had low capital cost but higher operating costs would be less competitive if mission scale or duration increased.

1.3.3. IDF Performance Assessment

The Performance Assessment (PA) for the Integrated Disposal Facility (IDF) was in progress but not finalized during most of the Supplemental LAW analysis. Any immobilized waste sent to IDF would need to meet these new requirements, but the lack of a final PA caused uncertainty in the evaluation for each waste form. Major changes were not expected from the drafts provided; therefore, the evaluation proceeded at risk using the values in the draft PA.

1.3.4 Programmatic Challenges with Using System Plan 8

A number of programmatic challenges, outside the scope of the review of Supplemental LAW, could impact the feed vector (both composition and volume). As stated above, the best estimate for the material to be processed through the Supplemental LAW facility is the current revision of the Integrated Flowsheet. This flowsheet is based on assumptions contained in System Plan 8²⁰. It is noted that System Plan 8 contains a number of different processing scenarios, 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 Supplemental LAW. 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 Supplemental LAW 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

²⁰ "River Protection Project System Plan," U.S. Department of Energy: Office of River Protection, Richland, Washington, ORP-11242, Rev 8, 2017.

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.²¹

1.4 TECHNICAL CHALLENGES

By setting the scope as immobilization of the feed vector determined from the Integrated Flowsheet, the evaluation of Supplemental LAW technologies becomes a well-defined task for the three immobilization technologies. Each immobilization technology has been previously evaluated and some testing performed for the Hanford tank waste. Vitrification and grout have been previously utilized at West Valley and the Savannah River Site while steam reforming is currently being planned for the Idaho Nuclear Technology and Engineering Center. Thus, determination of the technical feasibility of each immobilization technology becomes an exercise in comparing the known attributes of the treatment technology to the feed vector.

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

The immobilization technologies have been previously evaluated over a wide range of compositions that may sufficiently cover the range of compositions expected from the current feed vector. However, the prediction of long term performance for each waste form presents some challenges for compositions that vary significantly from compositions where initial studies of each technology were performed. The evaluation of each immobilization technology case and variant identifies when the feed vector would result in an immobilized product outside the bounds of previous testing and addresses the impact on the viability of that technology.

Developing realistic cost estimates for each technology involves uncertainty. 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 dramatically 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 will be 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."

1.5 COST ESTIMATION SUMMARY

The planning estimates for the proposed Supplemental LAW projects were developed from information mined from previous studies, current DOE facility construction projects, and current DOE operating facilities. Cost estimating was 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 Supplemental LAW process. Adjustments were made to

²¹ Kosson, D. S.; D. R. Gallay, I. L. Pegg, R. G. Wymer. "External Technical Review of System Planning for Low-Activity Waste Treatment at Hanford." November 2008.

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 Rough Order of Magnitude (ROM) comparison. The ROM estimate does not reflect the costs required to prepare tanks for transfer of materials to the new facility or for the final closure of any existing tank.

The FFRDC team's Project Management subject-matter experts 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.

While these estimates are considered Class 5 per DOE O 413.3A, "Program and Project Management for the Acquisition of Capital Assets," such preconceptual estimates with ranges are considered to be valuable tools for decision makers.²²

Appendix J provides a full discussion of the cost estimation.

Table 1-2 provides a summation of the cost estimate ranges for each base scope and its variant cases combined.

²² Need reference

Table 1-2 Preliminary Summation of Cost Numbers for Base and Variant Scopes Combined

	Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost*
VITRIFICATION									
	\$340M – \$1560M	\$1,000M – \$2,600M	\$680M – \$15,600M	\$1M – \$2.6M	\$10,080M – \$12,810M	N/A	\$10,000M – \$14,625M	\$1,421M – \$1,536M	\$27,000M – \$52,000M
FBSR									
	\$480M – \$1,100M	\$1,000M – \$2,600M	\$1,900M – \$6,880M	\$1M – \$2.6M	\$2,520M – \$4,914M	\$1,850M – \$2,775M	\$300M – \$690M	\$1,421M – \$1,536M	\$8,000M – \$19,000M
CAST STONE									
	\$90M – \$280M	N/A	\$500M – \$2,180M	\$1M – \$2.6M	\$1,120M – \$1,680M	\$2,775M – \$4,163M	\$250M – \$2,258M	\$142M – \$193M	\$2,100M – \$10,000M

*Total Program Cost is rounded.

NOTE: COSTS REQUIRE UPDATE. SEE TABLE 2 IN EXECUTIVE SUMMARY.

2.0 HANFORD LAW OVERVIEW

2.1 BASELINE PROCESS FOR HANFORD LAW AND SUPPLEMENTAL LAW IMMOBILIZATION

2.1.1 Summary

The Supplemental 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 HLW to WTP combined with LAW feed from tank farms and the supernate generated during HLW pretreatment (washing and leaching operations) is greater than the capacity of the current LAW vitrification facility. If the WTP processing is adjusted to not exceed the LAW capacity, then HLW processing would be reduced and the overall mission length would be extended.

The Supplemental LAW facility is expected to receive feed from two sources: LAWPS and the WTP PT. 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. Supplemental LAW 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.

2.1.2 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 waste stored at Hanford varies significantly in chemical and radionuclide content, although some incidental blending of the various wastes has occurred during storage.²³

The waste has been stored in 177 underground, carbon steel storage tanks. Many of these tanks are known to have developed leaks²⁴; 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.²⁵

The Hanford Waste Treatment and Immobilization Plant (WTP) is a complex of facilities²⁶ designed to receive waste from the storage tanks and perform all pretreatment processes to prepare the waste for immobilization

²³ Agnew, S.F.; J. Boyer, R.A. Corbun, T.B. Duran, J.R. FitzPatrick, T.P. Ortiz, and B.L. Young. "Hanford Tank Chemical and Radionuclide Inventories: HDW Model Rev. 4." LA-UR-96-3860. January 1997. Los Alamos National Laboratory. Los Alamos, New Mexico.

²⁴ Gephart, R.E. "A Short History of Hanford Tank Waste Generation, Storage, and Release." PNNL-13605. Rev. 4. 2003. Pacific Northwest National Laboratory. Richland, Washington.

²⁵ Smith, R.D. "Tank Farms Documented Safety Analysis." RPP-13033. Revision 7-G. 2017. Washington River Protection Solutions. Richland, Washington.

²⁶ Deng, Y.; B. Slettene, R. Fundak, R.C. Chen, M.R. Gross, R. Gimpel, and K. Jun. "Flowsheets Bases, Assumptions, and Requirements." 24590-WTP-RPT-PT-02-005. Rev 8. 2016. Bechtel National, Inc. River Protection Project. Waste Treatment Plant. Richland, Washington.

and then immobilize the waste in borosilicate glass.²⁷ A simplified diagram showing the tank farm, WTP, and other facilities required is shown in Figure 2.1.

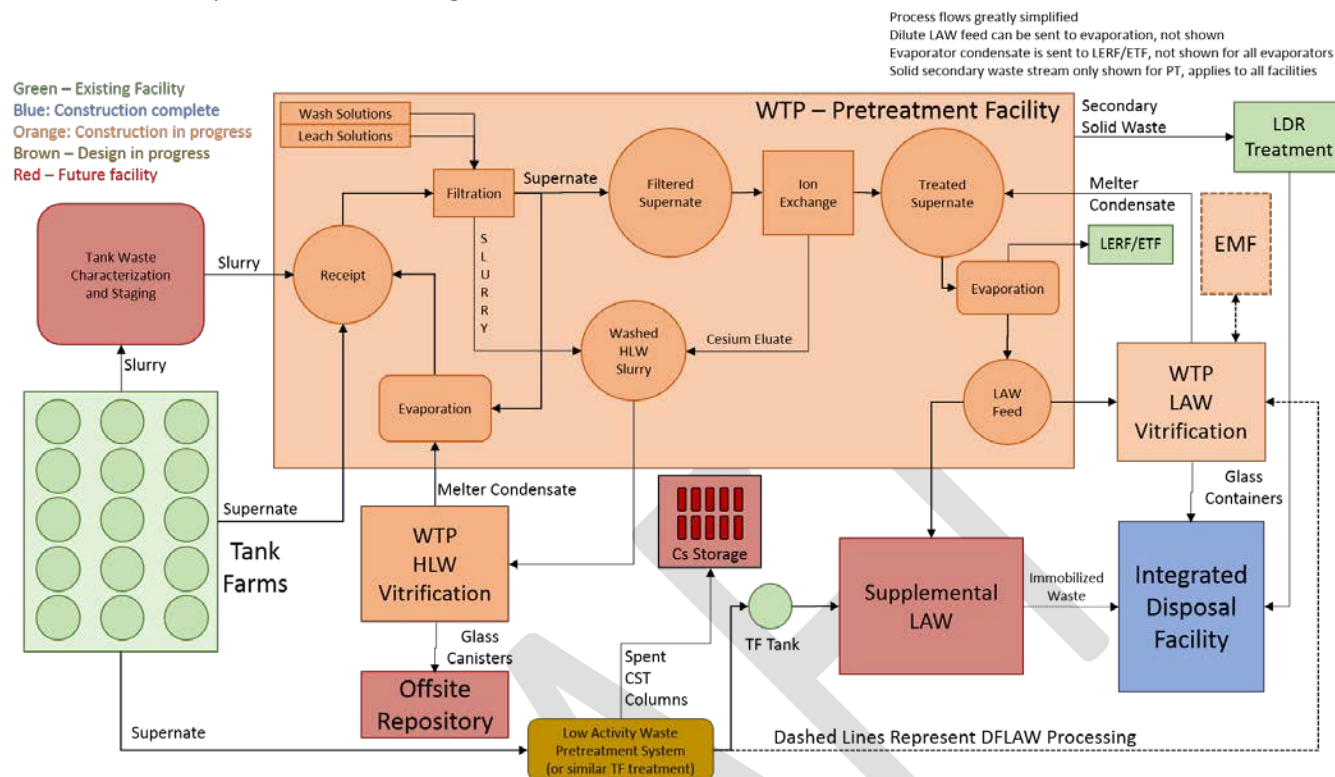


Figure 2-1 Simplified Flow Sheet for Immobilization of Hanford Waste during Full WTP Operation

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 Pretreatment Facility (PT). Supernate from the tank farms will be transferred directly to PT or the Low Activity Waste Pretreatment System (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 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 WTP LAW facility, the excess is sent to Supplemental LAW for immobilization. It is currently estimated that approximately 2/3 of the treated supernate will be sent to Supplemental LAW. It should be noted that the

²⁷ “River Protection Project System Plan.” ORP-11242. Rev 8. 2017. U.S. Department of Energy Office of River Protection. Richland, Washington

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 WTP 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 LAWPS facility to remove solids and cesium (using filtration and ion exchange similar to PT) with the treated supernate sent to Supplemental LAW.

2.1.2.1 Direct Feed Options

The LAWPS facility is expected to start operation prior to WTP PT and will feed WTP LAW vitrification until PT is started. Melter condensate will be handled by the Effluent Management Facility (not shown in Figure 2.1) during direct feeding of LAW from the LAWPS. Other processing options considered in the baseline flowsheet include adding the capability to directly feed the HLW vitrification from the Tank Waste Characterization and Staging Facility.²⁸

2.1.3 Baseline Supplemental LAW Process

A decision on the immobilization technology for Supplemental LAW 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”. The Integrated Flowsheet defines the function of Supplemental LAW 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 Supplemental LAW facility has two feed vectors in the current baseline flowsheet: Leftover LAW from PT and additional feed from LAWPS.²⁹ Supplemental LAW 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 Supplemental LAW. Supplemental LAW 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) while solid secondary waste is sent to treatment for land disposal (assumed to be encapsulation in grout with disposal at IDF) at the Land Disposal Restrictions (LDR) treatment facility. The immobilized waste from Supplemental LAW is assumed to be disposed at the IDF, but a final decision has not been made.

The interfaces between Supplemental LAW and other facilities 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.

²⁸ Cree, L.W.; 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. 2017. Washington River Protection Solutions (WRPS) One System. Richland, Washington.

²⁹Cree, L.H. “Re: Some Pending Requests for Help.” Email from Laura Cree to Michael E Stone. 2017.

2.2 FEED VECTOR

The Supplemental LAW feed vector³⁰ calculated for the One System River Protection Project Integrated Flowsheet³¹ will be used in the evaluation of the feasibility of proposed Supplemental LAW processes. This feed vector consists of 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 the Supplemental LAW 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 waste form generation as well as estimates for secondary waste stream generation, treatment, and disposal.

The assumptions made during flowsheet model runs (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 Supplemental LAW feed vector is the best currently available, the actual waste processed through Supplemental LAW could be significantly different from 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 Supplemental LAW facility. Thus, any Supplemental LAW 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 Supplemental LAW 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 from PT in the Integrated Flowsheet.

In addition, as a result of the unconstrained model and the desire to achieve full capacity through the HLW vitrification facility, the Supplemental LAW will also need to accommodate extremes in feed volume. 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 Supplemental LAW.

2.3 INTEGRATED FLOWSHEET

The One System Integrated Flowsheet was utilized as the source for the Supplemental LAW 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

³⁰ Cree, L.H. "Re: Some Pending Requests for Help." Email from Laura Cree to Michael E Stone. 2017.

³¹ Cree, L.W.; 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. 2017. Washington River Protection Solutions (WRPS) One System. Richland, Washington.

years. It is the only source identified that calculates the feed vector for Supplemental LAW 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 document³² which lists the calculational techniques and assumptions made in the calculations for each unit operation. See Appendix M, “Expanded Discussion: Feed Vector,” for additional discussion about TOPSim.

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 Supplemental LAW feeds to prevent the most extreme conditions noted in the current feed vector. Thus, a proposed flowsheet should not be automatically eliminated from consideration if a small set of conditions noted in the current vector are outside the ranges possible with the flowsheet.

2.4 SUMMARY OF STUDY BASES

The feed vector provided by WRPS³³ is the best information available and will be used to perform the assessment of proposed flowsheets for supplemental LAW disposition. The capacity of the Supplemental LAW facility should be based on the flowrates to Supplemental LAW 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.

³² Schubick, A.M.; 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. 2016. Washington River Protection Solutions. Richland, Washington.

³³ ³³ 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.

3.0 ANALYSIS RISK ASSESSMENT

3.1 INTRODUCTION

Risk Assessment is defined as a “systematic process of evaluating the potential risks that may be involved in a project activity or undertaking.”³⁴ The NDAA 3134 Supplemental Treatment Study evaluates potential risks as part of its evaluation of supplemental treatment technology alternatives. However, there are many aspects of risk that could be evaluated. This chapter describes those risks being considered within the FFRDC scope of the NDAA study, and the means being used to assess those risks, either qualitatively or quantitatively.

3.2 BACKGROUND

Risk assessment techniques can be applied at many different levels, and the term has different connotations when used in different applications. Three areas of risk assessment are particularly relevant to the NDAA study:

1. **Project Risks.** The Project Management Institute defines project risks as “an uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives.”³⁵ The effect is frequently on project costs and schedule. Identifying risks and their potential impact, as well as risk mitigation approaches is important to project planning and execution.
2. **Alternatives Risks.** Similar to risk assessment used in planning and executing specific projects, GAO defined best practices for assessing risks in the early project stage where alternatives are being evaluated – such as waste treatment technology alternatives. Best practices included 1) identifying and documenting “...the significant risks and mitigation strategies for each alternative,” and 2) testing and documenting the “...sensitivity of both cost and benefit/effectiveness estimates for each alternative to risks and changes in key assumptions.”³⁶
3. **Environmental Risk Assessment.** EPA defines risks to be the “chance of harmful effects to human health or to ecological systems resulting from exposure to an environmental stressor”, and describes environmental risk assessments as falling into either human health risk or ecological risk assessments.³⁷ Environmental risk assessment is an important aspect of DOE decision making in terms of both NEPA analysis (e.g., environmental review such as an EIS) performed to evaluate potential DOE alternatives, as well as performance assessment analysis required to operate and maintain DOE LLW disposal facilities.³⁸

3.3 APPLICATION OF RISK ASSESSMENT TECHNIQUES

The FFRDC team identified and evaluated risks principally in areas 2 and 3 above. Specifically, for each primary alternative being evaluated, the team identified and documented significant risks and assumptions that supported the evaluation of alternatives and enabled semi-quantitative risk assessment and estimation of the total cost of each alternative. The alternatives assessment was conducted in two primary steps—1) a preliminary assessment to screen the processing options being considered from a large list of alternatives and variants to a short list of key alternatives, and 2) a semi-quantitative risk assessment focused on the significant technical and

³⁴ “Risk Assessment.” *English – Oxford Living Dictionaries*. Oxford University Press. Undated.
https://en.oxforddictionaries.com/definition/risk_assessment. Web. 17 January 2018.

³⁵ *A Guide to the Project Management Body of Knowledge (PMBOK® Guide) – Fifth Edition*. 2013. Project Management Institute Inc.

³⁶ “GAO, DOE and NNSA Project Management: Analysis of Alternatives Could be Improved by Incorporating Best Practices.” GAO-15-37. 2014. U.S. Government Accountability Office.

³⁷ “About Risk Assessment.” Risk Assessment. United States Environmental Protection Agency.
<https://www.epa.gov/risk/about-risk-assessment#whatisrisk>. Web. 17 January 2018.

³⁸ “LFRG DOE Order 435.1.” Office of Environmental Management. U.S. Department of Energy. Undated.
<https://www.energy.gov/em/lfrg-doe-order-4351>. Web. 17 January 2018.

programmatic risks of each alternative. In addition, for the final disposal of the immobilized LAW, the team assessed the potential for compliance with disposal site waste acceptance criteria and performance objectives. Specific approaches applied to each of these risk assessment activities are described below.

3.3.1 Alternatives Evaluation and Risk Assessment

For each technology and its corresponding flowsheet, once narrowed to a finite list of options/alternatives and variants for consideration, the Team evaluated each option against a set of predefined lines of inquiry (LOIs) (aka, areas of consideration and corresponding assessment criteria). Each LOI has a pre-established set of qualitative metrics defined. A structured approach, the Analytic Hierarchy Process (AHP), was used to evaluate each option/alternative with the goal of screening more than 22 options/variants down to a short list of primary waste processing and disposal options for detailed analysis. Although the LOI contained risk criteria and metrics, this initial AHP evaluation was focused principally on alternatives screening rather than risk assessment. For further information and results of the AHP analysis to screen initial alternatives, see Appendix I.

A second step in the process involved further evaluation of the significant technical and programmatic risks associated with each waste processing and disposal option. 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, 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 was 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. Additional information on the risk analysis methodology and results can be found in [Appendix XX](#).

3.3.2 Disposal Waste Form Performance Evaluation

Onsite (Hanford) and commercial offsite (e.g., WCS) disposal is considered in the study. The disposal site Waste Acceptance Criteria (WAC) is the primary means of evaluating whether the immobilized wastes (primary and secondary) produced from each alternative process will be acceptable for disposal. In the case of commercial offsite disposal, there is a defined, final WAC that has been accepted and approved by the responsible regulatory agency. For the Integrated Disposal Facility (IDF) at Hanford, current WAC are documented within the RCRA dangerous waste permit³⁹. However, a final approved WAC has not yet been established. In addition, the permit currently limits ILAW disposal at IDF to vitrified (glass) waste forms from WTP and a demonstration bulk vitrification system. Therefore, to evaluate and compare the Study alternative waste forms on an “apples to apples” basis, an IDF waste form performance evaluation effort was conducted by the team to assess the potential performance of each alternative waste form in the IDF environment. This approach is very similar to that conducted in 2003 for the initial supplemental treatment alternatives assessment.⁴⁰

³⁹ Hanford Dangerous Waste Permit, Rev. 9. WA7 89000 8967, Part III Operating Unit Group 11, Integrated Disposal Facility Section III.11.C.5, Waste Acceptance Criteria and Waste Verification Requirements (<https://fortress.wa.gov/ecy/nwp/permitting/hdwp/Rev/9/OU/IDF.html>)

⁴⁰ 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.

The IDF waste form performance evaluation approach proposed for this assessment includes:

- Documentation of the waste form release mechanisms, waste form and disposal site assumptions including configuration, inventory of key contaminants, recharge/infiltration, barrier life, waste form release rate parameters, values, and basis, and modeling/assessment tools employed. A comparison of assumptions, mechanisms, and parameters used in the 2003 Risk Assessment⁴¹, 2014 EIS⁴², and 2017 Draft IDF Performance Assessment⁴³ is provided, along with a discussion of any differences in assumptions or input parameters used by the Study Team.
- Each waste form was modeled to the extent necessary to obtain release rate information for key contaminants of concern (CoCs) that have been identified from prior studies (e.g., Tc⁹⁹, I¹²⁹). The extent practical and achievable within the schedule and cost limitations of the study, a range of assumptions and parameter values were considered to assess the uncertainty in CoC release rates from the disposal facility (e.g., range of values).
- Groundwater impacts have been previously shown to be a primary area of concern relative to assessment of primary and secondary waste form disposal in IDF. Contaminant transport from the IDF to the groundwater and downgradient point of compliance is driven principally by the release rate from the IDF, and is assumed in this study, as in the 2003 Risk Assessment, to be insensitive to the waste form type which was the source of the contaminant. Therefore, analysis from prior studies, including the most recent 2017 IDF PA, is used to quantitatively translate IDF release rate to the potential environmental impacts to groundwater and human receptors (e.g., groundwater concentration and dose).

⁴² DOE. 2012. Tank Closure and Waste Management Environmental Impact Statement. DOE/RL-0391. U.S. Department of Energy, Richland, Washington.

⁴³ 2003 Risk Assessment, 2014 EIS, and DOE. 2017. Integrated Disposal Facility IDF Performance Assessment (DRAFT). RPP-RPT-59958, Rev. 1. Washington River Protection Solutions, Richland, Washington. (unpublished)

4.0 ASSESSMENT AREA SUMMARIES

4.1 VITRIFICATION

TBD

See full discussion in Appendix B.

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4.2 STEAM REFORMING

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 ResinSolutions Facility (formerly Studsvik Processing Facility) in Erwin, TN treats 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/>). Steam reforming has been tested at bench and pilot scales up to 24-in. diameter for treating various liquid radioactive wastes including Hanford LAW, Hanford WTP liquid secondary waste, Idaho National Laboratory (INL) sodium bearing waste (SBW), Savannah River Site Tank 48 waste, and waste streams for ORANO (formerly AREVA). The 48-in. diameter full-scale Idaho Waste Treatment Unit (IWTU) was constructed in 2012 for treating INL SBW. This facility has been in non-radioactive startup operations since then with the goal to complete startup and begin radioactive operations.

Steam reforming is a thermal process that operates at temperatures up to 725-750°C to evaporate water in the waste, destroy nitrates, destroy organics, and (for treatment of Hanford SLAW) convert the solid residue into a durable, leach-resistant waste form. This 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 up through the fluidized 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 (a) heat the DMR to the target operating temperature, and (b) produce H₂ and other reduced gas species such as CO and CH₄ that react with the nitrates and nitrites in the waste feed, converting the nitrates and nitrites to N₂ and H₂O. Organics in the feed are efficiently pyrolyzed, nitrates in the feed are destroyed to below detectable levels, and about 95-99% of the NO_x is 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 (WF) to form the desired mineralized waste form. This product includes highly durable mineral structures of (a) nepheline (nominally NaAlSiO₄), (b) sodalite [nominally M₈(Al₆Si₆O₂₄)X₂, where M is an alkali cation such as Cs, K, Na, etc. and X is an anion or oxyanion, such as Br⁻, Cl⁻, I⁻, TcO₄⁻, or SO₄⁻²], (c) nosean (nominally Na₈[AlSiO₄]₆SO₄ with a larger cubic sodalite structure), and (d) carnegieite (nominally orthorhombic NaAlSiO₄). These nepheline, carnegieite, sodalite, and nosean 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 (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015]).

4.2.1 FBSR Process Options

Two FBSR options are proposed, along with a third alternative option. Case 1 (Figure 4.2-1) provides a durable, mineralized waste form for storage and permanent disposal in the 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.

Two process systems fed from a single feed system provide the needed throughput and ability to vary the throughput as needed to maintain the SLAW feed vector. The highest sustained waste feedrates occur in the first three years of SLAW treatment operations. After those first three years, the feedrate varies by over 50x turndown ratio (the ratio of the highest and lowest monthly feedrates and compositions).

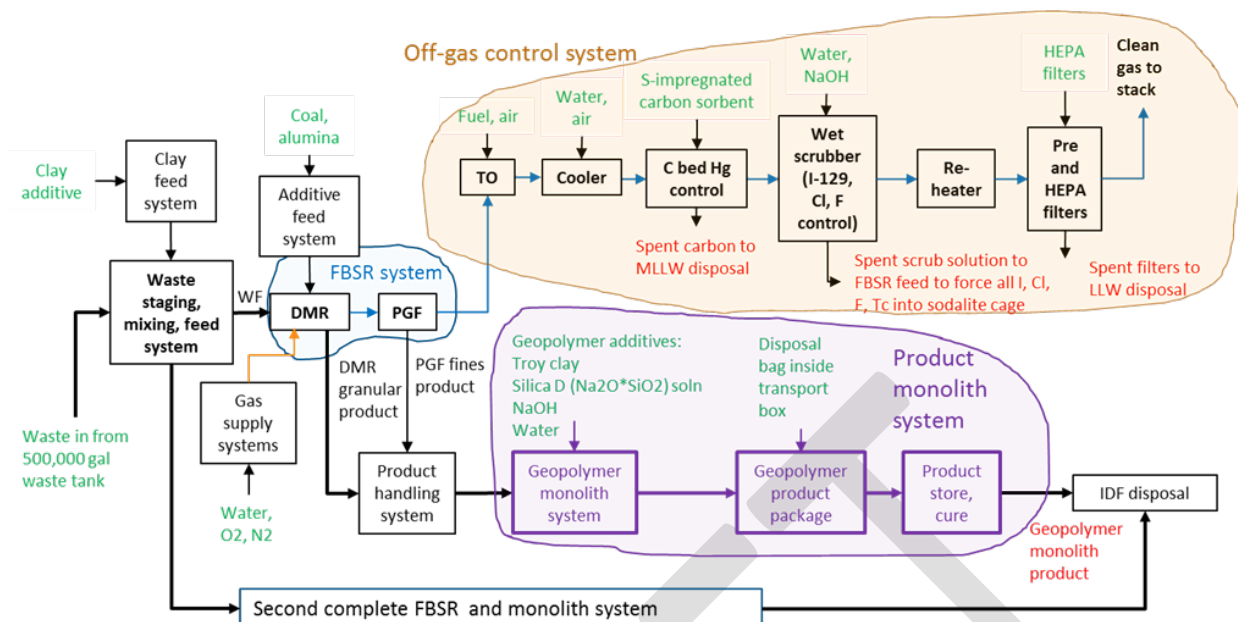


Figure 4.2-1. Case 1 Mineralizing FBSR, solid monolith product disposed at IDF (secondary wastes also disposed at IDF).

Figure 4.2-2 shows the Case 2 option, which is identical to Case 1 except the primary and secondary waste forms are shipped to WCS in Texas. WCS does not require a monolith waste form, and so the geopolymer monolithing system is eliminated, making the Case 2 processing facility simpler.

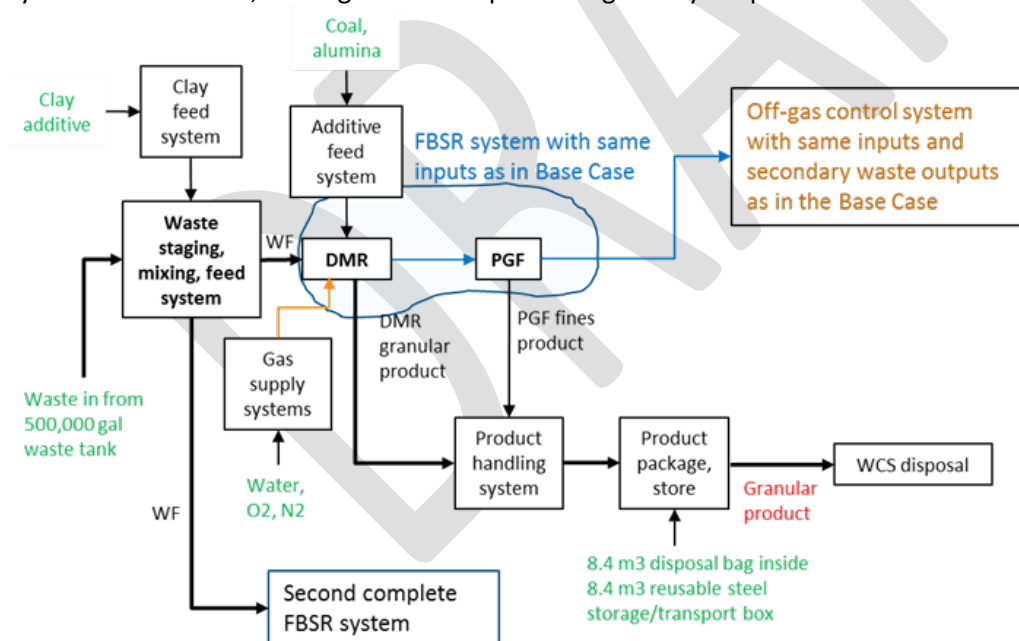


Figure 4.2.2. Case 2, Mineralizing FBSR to WCS; granular solid product disposed at WCF (secondary wastes also disposed at WCF).

These two cases bound the potential disposal options considered in this study. A variation on Case 1 (disposal in IDF) is elimination of the monolithing system by the use of High Integrity Containers (HICs) that provide the compressive strength instead of the monolith process. Other variations on Case 1 include shipping the

secondary wastes to WCS instead of placement in IDF. Variations on Case 2 could include disposal of some of either primary or secondary wastes in other out-of-state LLW disposal sites.

4.2.2 FBSR Mass and Energy Balance

A mass and energy balance using HSC Chemistry with Excel inputs and outputs tracks the fate of 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. Results for the average feed vector are shown in Figure 4.2-3. This is the same model that is currently used to track the performance and mass balance of the IWTU FBSR system. References for inputs to this model for the Hanford Supplemental LAW 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 2009), and the FBSR mineral waste form downselect report (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

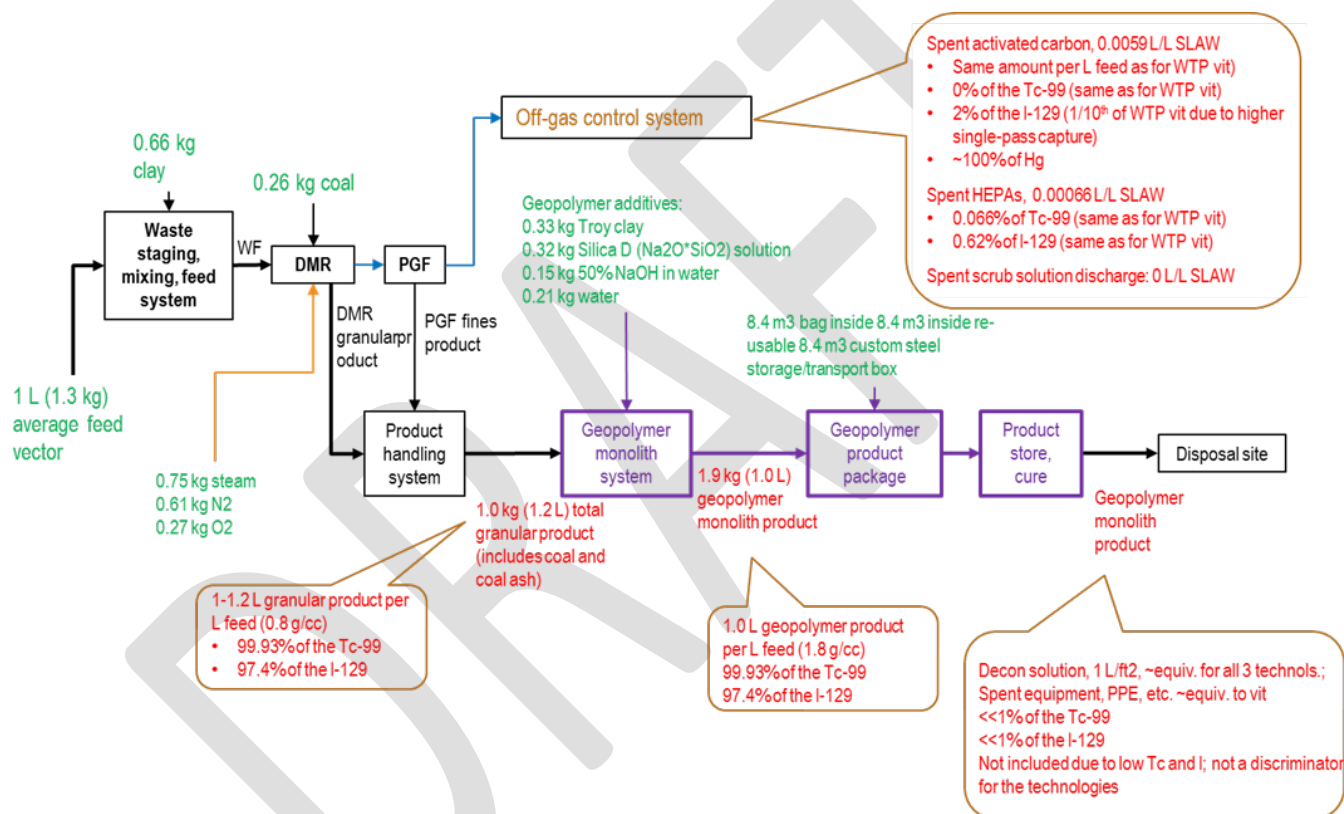


Figure 0.2-3. FBSR mass and energy balance for the average feed vector.

This 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. Key mass balance parameters normalized per 1 liter of average feed vector include:

- 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. This could be reduced to about 0.8 kg (1 L) if the amount of incompletely reacted coal could be reduced.
- 1.8 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.

4.2.3 Process Safety

As a thermochemical process, steam reforming has various risks normally associated with thermal processes. These risks are mitigated by methods established and proven in nuclear and other industries as shown in Tables 4.2-1 and 4.2-2.

Table 4.2-1. 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 4.2-2. Air emissions compliance.

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

4.2.4 Confidence that the FBSR Process will Work – Technology Readiness Level

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 by the team at a medium TRL for this particular use for treating Hanford SLAW. While the Erwin ResinSolutions 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 ResinSolutions 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 its 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 troubleshooting 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 ResinSolutions Facility and the IWTU because of the goal to produce the durable mineral waste form 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.

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.

4.2.5 Cost and Schedule

The costs for the Hanford SLAW FBSR concept are shown in Table D-4. The detail of these costs are provided in the cost estimating sections of this report and Appendix D.

Table 4.2-3. Estimated costs for the FBSR Cases 1 and 2.

Tech Dev	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replace	D&D	Total Program Cost
Case 1 - IDF								
\$480M – \$1,100M	\$1,000M – \$2,600M	\$1,900M – \$4,400M	\$1M – \$2.6M	\$3,300M– \$4,900M	N/A	\$300M – \$690M	\$TBD	\$8,500M– \$15,000M
Case 2 - WCS								
\$480M – \$1,100M	\$1,000M – \$2,600M	\$1,900M – \$6,900M	N/A	\$2,500M– \$3,800M	\$1,900M– \$2,800M	\$300M – \$690M	\$TBD	\$9,500M– \$19,000M

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 (2018) is 13 years, although six 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.

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.

4.2.6 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 ResinSolutions facility. But the 2012 Hanford tank closure and waste management environmental impact statement (TC and WM EIS, DOE 2012) concluded, among other things, that “...The steam reformed waste form would not be equal to that of the WTP glass...” Other documents contemporaneous to the 2012 EIS drew different conclusions. The National Research Council “Waste Forms Technology and Performance, Final Report,” (NRC 2011) concludes “...crystalline ceramic waste forms

produced by fluidized bed steam reforming have good radionuclide retention properties and waste loadings comparable to, or greater than, borosilicate glass. This waste form 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 waste form 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 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).

At least two issues remain. Permitting of non-glass waste forms in the IDF have not been done. First, and prior to and during the course of this study, most local and state level stakeholders have expressed strong opinions against non-glass waste forms for the SLAW. Second, many of these stakeholders have referred to, or used, the phrase “good as glass” when describing the candidate waste forms. Some scientists and stakeholders have different opinions about how waste form performance tests should be applied to non-glass waste forms. For example, while NRC 2011 recommends some performance tests for non-glass waste forms, Schepens 2003 states that some of those same performance tests are not suitable for non-glass waste forms. This issue may need additional investigation and resolution to provide a more widely accepted basis for demonstrating the performance of non-glass waste forms. This type of resolution, together with IDF performance assessments for non-glass waste forms, may be needed to obtain more acceptance of non-glass waste forms for the SLAW.

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 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.

Transportation of steam reformer LLW residues from the Erwin Resin *Solutions* facility has already been established. The mineral product transportation concept for the Hanford SLAW has been modeled after this approach.

4.2.7 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 waste form performance to enable stakeholders to consider if the mineralized waste form 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. Other risks, and how these risks are mitigated, are described in Appendix D.

4.2.8 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.
- The FBSR thermal process can meet BDAT requirements similar to vitrification and efficiently destroy hazardous organics, nitrates and NO_x, and ammonium compounds.
- According to recent waste tests, produce a durable waste form without increasing waste volume during treatment, and without produce any liquid secondary process that also require treatment, conversion to a waste form, and disposal.

4.2.9 Potential Opportunities for FBSR

Potential opportunities for steam reforming the Hanford SLAW include:

- Reducing or eliminating the “flywheel” concentrations of volatile and semivolatile elements by recycling scrub solutions less to WTP vitrification and more to SLAW steam reforming with higher single pass control efficiencies.
- 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 waste form with a ~2-100x lower-volume, durable mineralized waste form.
- 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.

4.2.10 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 waste forms.
- Develop consensus on how to assess performance of non-glass waste forms.
- Update conclusions of the 2012 TC and WM EIS to account for new steam reforming waste form 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 waste forms 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.

4.2.11 References

- DOE 2012, “Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington, (TC & WM EIS),” DOE/EIS-0391, November.
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NRC 2011, "Waste Forms Technology and Performance, Final Report," National Research Council of the National Academies, Committee on Waste Forms Technology and Performance, National Academies Press, Washington, DC.

Schepens, Roy J., 2003, DOE ORP letter to Michael A. Wilson, 03-ED-091, June 12.

TTT, 2009, "Report for Treating Hanford LAW and WTP SW Simulants: Pilot Plant Mineralizing Flowsheet," Project number 29387, Document number RT-21-002, Revision 1, April 2009.

See full discussion in Appendix C.

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4.3 GROUT

4.3.1 Summary

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; however, additional R&D would improve the understanding of these retention properties. **[NEED TO ADD SOMETHING ON TOM'S STUFF]** Two grout cases were assessed in detail: grout case I assumed IDF for final disposal, whereas grout case II assumed the WCS facility (TX) for final disposal. Costs associated with constructing and operating a Cast-Stone based grout facility are estimated to be in the range \$5–10B, and the time to hot start up is estimated to be 8–13 years. Several potential risks were assessed, and mitigation options exist for each. Grouted supplemental LAW would face no regulatory hurdles, except permitting at the IDF.

4.3.2 Overview of Grout and Cast Stone

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. Grout technology has a long history of being used to transform radioactive aqueous liquid and sludge waste streams into solid waste forms for disposal at ambient temperature or near ambient temperature.

Grout technology can be tailored for a range of waste chemistries, available cement ingredients, and process and final waste form 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. In other words, 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 Cast Stone processes considered in this analysis, the slurry is instead pumped into smaller containers ($\sim 10 \text{ m}^3$), where it is allowed to solidify before being transferred to the final disposal location. In this assessment, large disposal units are addressed briefly as a potential alternative if grout disposal occurs at or near the Integrated Disposal Facility.)

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). 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 constituents of potential concern (COPCs) within the solidified monolith, limiting release to the environment. Cast-Stone, in particular, has been tailored to have additional

favorable properties for LAW—such as establishing a reducing environment inside of the monolith that minimizes the mobility of some COPCs, e.g., technetium and chromium.

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. 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.

4.3.3 Retention Characteristics of Cast Stone

A primary focus for this assessment of grout-based systems has been whether the waste form would be likely to perform sufficiently well with respect to retaining COPCs that may be present in supplemental LAW. In particular, anionic species of radionuclides (iodine and oxidized forms of technetium) were of particular interest, due to previous assessments of grout 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 assessed these more recent studies and explored the implications of these studies on the retention characteristics of Cast Stone with respect to supplemental LAW.

Past assessments of grout performance have assumed that the release of constituents of potential concern (COPCs) is controlled by advective and diffusive processes (*physical retention*). In these types of assessments, the diffusion coefficients are primary direct factors in determining release rates, with small diffusion coefficients resulting in higher retention. Recent research has suggested there may, in fact, be some incorporation of at least technetium into solid phases, which improves long-term retention in the waste form. In addition, variations to the Cast-Stone formulation have also been considered in recent studies, such as the incorporation of additional reagents (known as getters) that can preferentially bind technetium and iodine into a solid form. Assessment based on advection-diffusion attempt to account for these phenomena using distribution coefficients or retardation factors that lower the diffusion coefficients in response to *chemical-retention* processes. The resulting parameters have been termed apparent diffusion coefficients.

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., ⁹⁹Tc release predicted by Mann, et al., 2003). However, recent studies have reported significantly lower 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).

For iodine, apparent diffusion coefficients 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). These studies show a spread in diffusion coefficients of ~10x for both iodine and nitrate, implying that the physical properties of Cast Stone can vary (perhaps offering an opportunity to optimize mix design/process for optimal retention). Some studies (Qafoku et al., 2014; 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.

For technetium, apparent diffusion coefficients in a Cast-Stone matrix are significantly lower than those for iodine or nitrate and significantly lower than values used in earlier assessments (Westsik, et al., 2013a; Cantrell, et al., 2016; Serne, et al., 2016). This lower apparent diffusion coefficient for technetium reflects chemical retardation effects in the matrix created by Cast Stone, most likely reflecting the reducing conditions created by the blast furnace slag. These studies show a spread in diffusion coefficients for technetium of ~100x, significantly larger than for iodine or nitrate; this spread implies that in addition to the variability in physical properties there can be variability in chemical properties. Additional research on the cause of this variability and on factors that could impact retention characteristics (e.g., oxidation rates under different scenarios) would lead to a better understanding of how to optimize the retention properties of Cast-Stone monoliths with respect to technetium as well as leading to a better understanding of long-term performance. Some studies (Qafoku et al., 2014; Asmussen, et al., 2018) have also shown that chemical retardation of technetium can be enhanced by the incorporation of technetium getters into the Cast-Stone process, which can lower the apparent diffusion coefficient for technetium by as much as a factor of 10.

The implications of these new data on diffusion coefficients relative to retention of technetium and iodine in a Cast-Stone monolith were explored using an advection-diffusion model. **[NEED TO INSERT DETAILS AND RESULTS FROM TOM ET AL. WORK HERE]**

4.3.4 Grout Cases Considered

This assessment considered to general cases for a grout process for supplemental LAW: one case assumed disposal of the primary grouted waste form at the Integrated Disposal Facility, and one case assumed disposal of the primary grouted waste form at the WCS facility in Texas. Detailed discussions of the cases (including process flow diagrams) are presented in Appendix E.

Both grout 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 supplemental LAW 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 m³ 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 low temperature nature of the process (minimal off gas) and the incorporation of liquids into the primary waste form (minimal-to-no liquid secondary waste stream). Hence, essentially all of the waste inventory resides in the primary waste form.

Both grout cases recognized the potential 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, grout 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 supplemental LAW; however, several possible pretreatment options were evaluated (see Appendix B). Pretreatment in the context of solidification of supplemental LAW 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 LAW vitrification facility, sending only organic-poor liquids to a grout facility. This would eliminate the need for pretreatment. Hence, the potential presence of LDR organics was recognized as an important consideration for both grout cases, but it does not appear to be a major impediment. LDR metals—which also represent a consideration for both grout cases—is less of a factor, because grout has been shown to be an effective waste form; indeed, several studies on Cast Stone have shown that at least some LAW waste streams can pass TCLP.

4.3.5 Assumptions

The primary assumptions in the analysis of the grout cases included the following:

- *The ranges and averages in feed vector composition are adequately captured by the One System Integrated Flowsheet.* 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 supplemental LAW 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 would eliminate the need for an organics pretreatment step.
- *Recent data showing lower values in release of Tc/I 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. [THIS STATEMENT NEEDS TO BE ASSESSED AFTER THE FINAL RESULTS ARE AVAILABLE FROM THE RELEASE CALCULATIONS BY TOM ET AL.]*

4.3.6 Risks

The primary risk identified for selecting a Cast-Stone process for supplemental LAW is the acceptability of the waste form at the IDF. Acceptability for WCS is not a risk, because WCS has a Federal Waste Disposal Facility already licensed to accept Class A, B, and C low-level waste and mixed low-level waste. However, grout waste forms have not been permitted for disposal at the IDF, and the State of Washington has explicitly questioned the use of a grout waste form. 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 waste form
- The removal (by pretreatment) of radionuclides of potential concern (Tc and I).

The first of these mitigation options is based on the recent studies on the retention properties of Cast Stone (Section 4.3.3), which suggest a significantly better performance for Cast-Stone monoliths relative to previous assessments of grout performance.

The potential presence of LDR organics is another risk for both grout cases, because both 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.

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

4.3.7 Benefits and Costs

Benefits of grout as an option to address supplemental LAW include:

- Less off-gas, hence less secondary waste.
- Start/stop flexibility, which can accommodate variations in feed-vector
- Elimination of potential worker safety concerns associated with high temperature processes
- Least-complex process of three options considered
- Lowest secondary waste volume due to minimal off-gas treatment and no liquid secondary waste stream

Cost estimates for the grout process are detailed in Appendix J. Grout has the lowest estimated costs among the options evaluated, ranging from ~\$2–10 B for grout cases I (IDF) and II (WCS).

4.3.8 Schedule

For a 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.

4.3.9 Regulatory Compliance

Grouted supplemental LAW 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 compliant with class B.

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

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 waste forms 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.

Grouted supplemental LAW would comply with the waste acceptance criteria for the WCS facility. Grouted supplemental LAW is not currently permitted at the IDF facility.

4.3.10 Obstacles

Obstacles for grout as an option to address SLAW include:

- *Grout is not permitted at IDF.* This obstacle applies only to grout case I (disposal at IDF).
- *Acceptable grout performance needs to be demonstrated.* This obstacle also applies only to grout case I. 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.

See full discussion in Appendix D.

4.4 PRETREATMENT

TBD

See full discussion in Appendix E.

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4.5 OTHER APPROACHES

TBD

See full discussion in Appendix F.

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5.0 SUMMARY OF DISPOSAL SITE CONSIDERATIONS

5.1 INTRODUCTION

Two disposal facilities are being considered for disposal of the immobilized secondary LAW (SLAW). The first facility, the Integrated Disposal Facility (IDF), is on-site at Hanford and is still being developed by the DOE. The second disposal facility, the Waste Control Specialists (WCS) facility, is off-site and is a commercially-operated disposal facility licensed by the State of Texas (a US Nuclear Regulatory Commission Agreement State⁴⁴).

These facilities are very different, not only in their ownership, but also in their physical setting and in their stage of development. There is a drinking water aquifer about 300 feet (90 m) beneath the IDF and over long timeframes radionuclides could leach to the groundwater, and it may be necessary to limit the quantities of long-lived mobile nuclides disposed in the IDF. Further, the IDF is still being studied and only preliminary conclusions can be made about the ability of the IDF to accept Grout Case II, Steam Reformed Case II and secondary waste forms (WFs).

Because there is no drinking water aquifer beneath the WCS facility, the disposal limits for long-lived mobile nuclides (such as Tc-99 and I-129) are not to protect the groundwater and the limits are solely to protect an individual who might inadvertently dig into the buried wastes after a loss of active and passive controls in the far future. Further, WCS has well-defined radiological waste acceptance criteria, which allows this study to determine how the immobilized SLAW WFs will classify for disposal at their facility.

This Section is divided into three major subsections and begins with a review of the characteristics of the SLAW requiring disposal, followed by a subsection addressing disposal at the IDF and a subsection addressing disposal at the WCS facility in west Texas. For this analysis, current conditions are assumed to prevail. Basing the analysis on current conditions prevents undue speculation about future conditions, while allowing an even-handed comparison of disposal at the two facilities.

5.2 WASTE FORM CHARACTERISTICS IMPORTANT FOR DISPOSAL

The characteristics of the SLAW that will be immobilized are described by the Feed Vector which is discussed in detail in Section 2.2. The Feed Vector provides monthly data on the characteristics of the liquid SLAW from the two pretreatment facilities, the WTP-PT and the LAWPS, over a 28-year period from December 2034 through January 2063 (a total of 337 months⁴⁵). If both pretreatment facilities (WTP-PT and LAWPS) operated every month over the 337 months, there would be 674 combined months of operations; however, neither facility operates full-time, and there are 441 combined months of operations, with the 441 discrete sets of data in the Feed Vector.

Importantly, the maximum resolution available in the Feed Vector is the monthly values –no greater resolution is available. The information in the Feed Vector includes:

- The monthly volume of SLAW produced by pretreatment in the WTP-PT and in the LAWPS
- The specific activity of 47 nuclides for each month of production, from each facility, and
- The total volume of all SLAW to be immobilized is 54,000,000 gallons (204,400 m³).

⁴⁴ Agreement States are states that have been granted specific regulatory authority by the US Nuclear Regulatory Commission, as allowed by Section 274 of the Atomic Energy Act of 1954, as amended.

⁴⁵ It is assumed that the small volumes of Feed from the WTP-PT, for January 2034 and February 2034, would be held in the 500,000-gallon waste feed delay tank, and combined with the Feed from December 2034 when continuous immobilization activities begin.

The characteristics of the SLAW will be changed by the immobilization process. Grouting, steam reforming and vitrification will each causes different changes the SLAW. Table 5-1 describes how Grouting Case II would change the characteristics of the SLAW Feed, and the characteristics the final Grout Case II WF. Tables in Appendix G provide similar information for Steam Reforming and Vitrification.

Table 5-1 Characteristics of Grouted Waste Form Case II

Volume change caused by grouting	1.8 (grouting increases volume & decreases specific activities)
Density of final grout WF	1770 kg per cubic meter (/m3) or 110 lb per cubic foot
Total volume of grout (204,400 m3 x 1.8)	367,900 m3
Average monthly volume (total/337 months)	1092 m3 / month

5.3 INTEGRATED DISPOSAL FACILITY

Located in the 200 East Area of Hanford, the DOE is developing the IDF to provide a disposal facility for the Immobilized Low Activity Waste from the WTP, SLAW, and other related wastes (see Figure 5-1). Key site characteristics here?

The IDF currently consist of two disposal cells, although the facility can be expanded as needed to a total capacity of six cells. The IDF is a double-lined landfill that has a leachate collection and removal system that have secondary containment and leak detection systems.

Cell 1 is for radioactive MLLW that contains dangerous or hazardous waste and is regulated under RCRA by Washington State Department of Ecology. The DOE regulates the radioactive component⁴⁶ of wastes going to the IDF under DOE's Order 435.1. The DOE and Washington State Department of Ecology agreed that they would complete one Performance Assessment for the IDF that would satisfy the requirements of both DOE O 435.1 and RCRA. Before disposal, all waste must meet LDR requirements in 40 CFR 268. The radiological component of the Waste Acceptance Criteria (WAC) for the IDF is still being finalized and will depend, in part, on the results of the Performance Assessment.



Figure 5-1. Aerial View of the Two IDF Cells in the Hanford Site 200-East Area Southwest of WTP.

Disposal Performance Evaluation

- Analysis Approach and benchmarking against the PA
- Results from the Evaluation
- Key conclusions

5.4 WASTE CONTROL SPECIALISTS

⁴⁶ In implementing the Safe Drinking Water Act, Washington State Department of Ecology regulates some of the radioactive wastes going to the IDF.

Waste Control Specialists, LLC is a treatment, storage and disposal company whose primary facilities are located 35 miles (56 km) west of Andrews, Texas. The area surrounding WCS's facilities is sparsely-populated, and on average receives less than 16 inches (400 mm) of rainfall per year. The facilities are underlain by 600-foot (185-m) thick red-bed clays. Because of these thick red-bed clays, there is no drinking water aquifer beneath or adjacent to WCS's facilities. Their facilities include the **Federal Waste Disposal Facility (FWF)** which was designed, licensed, and constructed for disposal of "federal" radioactive wastes. This study assumes use of the FWF which is shown in Figure 5-2.

At WCS, 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. The FWF is licensed for up to 736,000 m³ of wastes, which is roughly twice the total volume of the grouted SLAW. Higher-activity Class B and C wastes are disposed in Modular Concrete Canisters inside the disposal cell.

To facilitate waste handling, this study assumes the primary WFs will be packaged, shipped and disposed using shipping containers with a capacity of 8.4 m³ each (11 yards³); with two shipping containers fitting in a standard Modular Concrete Canister.



Figure 5-2 A Waste Control Specialists Disposal Cell and Wastes Being Placed in Modular Concrete Canisters (note workers for scale)

The Texas Commission on Environmental Quality licensed the FWF. The license utilizes the NRC's LLW classification system (see 10 CFR 61.55) which divides wastes into Class A, B and C for disposal. Class A wastes are the least hazardous and Class C wastes are the most hazardous. The natural barriers (e.g., no drinking water aquifer and thick red-bed clays) and the engineered barriers (e.g., the Modular Concrete Canisters) work together to give the FWF one of the most robust multi-barrier designs of any Agreement State-licensed LLW disposal facility in the United States.

Waste must meet WCS's Waste Acceptance Criteria or WAC, before being accepted for disposal. One of these criteria is that RCRA LDR requirements in 40 CFR 268 must be met. As a thermal process, it is assumed Steam Reforming Case II WF will meet the LDRs, but Grout Case II WF will require pretreatment to meet LDRs.

The radiological WAC for the FWF are defined by two tables in WCS's *FWF Generators Handbook*. These two tables are reproduced in Appendix G of this study. The disposal of wastes from Hanford containing Tc-99 is not an issue at WCS because their Class C WAC for Tc-99 is 3 Ci/m³ and the average concentration of Tc-99 in the SLAW Feed Vector is 0.05 Ci/m³ (roughly one one-hundredth the limit). The same is true for the I-129 in the SLAW, as the average concentration of I-129 in the SLAW Feed is roughly one one-thousandth of WCS's Class C limit.

An EXCEL workbook has been developed as a part of this study, and in the workbook the SLAW Feed Vector radiological concentrations can be modified to match the characteristics of the final immobilized WF. Using the Feed Vector Data with its monthly radiological concentrations, and data on the characteristics of the final immobilized WF and the radiological WAC for WCS, the workbook classified all 441 discrete sets of monthly Feed Vector data for the SLAW Feed for Grout Case II and Steam Reforming Case II.

Based on this analysis, all the primary Grout Case II WFs will classify as Class B (about 92%) and Class C (about 8%) for disposal at WCS. The primary WF from Steam Reformed Case II will classify higher than for grout, with about 68% classifying as Class B and about 30% classifying as Class C. Two percent of the Steam Reformed Case II mineral product will classify as Greater-than-Class C, which WCS cannot accept. Analysis presented in Appendix G demonstrates that local mixing,⁴⁷ before Steam Reforming, can be used to prevent the generation of Greater-than-Class C wastes.

In addition to the primary WFs (with the majority of the volume), three secondary WFs will be generated: (1) during the operation of any immobilization facilities, or (2) in a pretreatment process that operates before final immobilization. The volume and curie content of these WFs is summarized in Table G-12 in Appendix G. The Solid Secondary Wastes (containing operational HEPA air filters and granular activated carbon) and the solidified Liquid Secondary Wastes from Vitrification are analyzed in Appendix G, and all will Classify as Class A for disposal at WCS. 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 which is approximately 5% of the volume of the Vitrified WF. If a hybrid approach is desired, such as a Vitrified WF to the IDF and solidified Liquid Secondary Wastes to the WCS, the Liquid Secondary Wastes would be Class A and of a relatively small volume.

In an alternative analysis for grout (option 2e2) Pretreatment Waste containing concentrated Tc-99 and I-129 would be grouted and sent to WCS for disposal, while the primary Grout WF would be disposed onsite in the IDF. These Pretreatment Wastes would be managed as Class C, with the volume of the Tc-99-bearing wastes being about 4,280 m3. If a hybrid approach is desired, such as grout to the IDF with the Tc-99 and I-129 removed in pretreatment and sent to WCS for disposal, the Pretreatment Wastes would be Class C and of a relatively small volume.

Based on their existing disposal fees, and discussions with WCS, it is assumed for this Study that the disposal fees at WCS for the primary WFs would be (1) \$1370/m3 for Class A MLLW and (2) \$5220/m3 for the Class B and C MLLW. As shown in Table 5-2, the disposal fees were used to calculate the disposal costs based on the volumes and waste classifications. These disposal costs are not the full cost of disposal, as wastes must be properly characterized, packaged and shipped to WCS.

Table 5-2 Disposal Costs based on the Volume, Waste Classification and Disposal Fees at WCS.

Waste Form	Total Volume	Waste Classification	Disposal Costs
Grout Case II with LDR pretreat (2g2)	367,900 m3	Class B and C	\$1.9 B
Steam Reformed Case II (3b)	245,300 m3	Class B and C	\$1.3 B

The key take-away from the detailed analysis presented here and in Appendix G is that the Grout Case II WF and the Steam Reformed Case II WF, and select Secondary Wastes, can be accepted for disposal at the WCS disposal facility (assuming some local pre-mixing for Steam Reforming Case II and that pre-treatment will allow Grout Case II to meet LDRs).

See full discussion in Appendix G.

⁴⁷ Local mixing is the mixing together of SLAW from WTP-PT and LAWPS before immobilization, and the mixing of SLAW Feed from adjacent months before immobilization (e.g., mixing the Feed from March 2035 with the Feed from November 2035) in the 500,000-gallon waste feed delay tank.

6.0 SUMMARY OF TRANSPORTATION CONSIDERATIONS

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See full discussion in Appendix H

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APPENDIX A. APPLICATION OF GAO BEST PRACTICES FOR THE ANALYSIS OF ALTERNATIVES

As shown in the table below, the FFRDC team used the “Best Practices for the Analysis of Alternatives” established by the United States Government Accountability Office (GAO)⁴⁸ as general guidelines for the analysis of alternatives for supplemental treatment of low-activity waste (LAW) at the Department of Energy’s (DOE’s) Hanford Nuclear Reservation.

GAO 24 Steps	Description	Assessment
Process Included in the General Principle Category		
1	The customer defines the mission need and functional requirements without a predetermined solution.	The mission need is per NDAA for 2017, Section 3134, “Analysis of Approaches for Supplemental Treatment of Low-Activity Waste at Hanford Nuclear Reservation.” Including potential “other” technologies precludes a predetermined solution.
2	The customer defines functional requirements based on the mission need.	Functional requirements are per NDAA for 2017, Section 3134. “Analysis of Approaches for Supplemental Treatment of Low-Activity Waste at Hanford Nuclear Reservation.”
3	The customer provides the team conducting the analysis of alternatives (AOA) with enough time to complete the AOA process to ensure a robust and complete analysis.	The FFRDC team completed the AOA over a time span of approximately two years, which is sufficient for this study.
4	The team includes members with diverse areas of expertise including, at a minimum, subject matter expertise, project management, cost estimating, and risk management.	The team consisted of members with diverse areas of expertise, identified by the Department of Energy (DOE) Office of Environmental Management (EM) National Laboratory Network (EMNLN). Biographies of the members are included in the package.
5	The team creates a plan, including proposed methodologies, for identifying, analyzing, and selecting alternatives, before beginning the AOA process.	A Program Plan, SRNL-RP-2017-00242, “Program Plan for Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation,” was developed to identify the approach to the analysis of alternatives. Some details of risk analysis evolved during the study.
6	The team documents all steps taken to identify, analyze, and select alternatives in a single document.	This report documents all steps pertinent to the selection of alternatives and includes descriptions of the alternative cases.
Process Included in the General Principle Category (continued)		

⁴⁸ DOE AND NNSA Project Management: Analysis of Alternatives Could Be Improved by Incorporating Best Practices. GAO-15-37. December 2014. Report to the Committee on Armed Services, U.S. Senate. United States Government Accountability Office.

7	The team documents and justifies all assumptions and constraints used in the analysis.	Each alternative case developed includes a section documenting key assumptions and constraints.
8	The team conducts the analysis without a predetermined solution.	The analysis includes 12 cases and no predetermined solution or recommendation.
Process Included in the Identifying Alternatives Category		
9	The team identifies and considers a diverse range of alternatives to meet the mission need.	The analysis includes 12 cases and a discussion of others considered but not matured.
10	The team describes alternatives in sufficient detail to allow for robust analysis.	The team described the alternatives considered in detail, including providing descriptions of the specific characteristics of each alternative used to create cost estimates as well as flowsheets. Details are included in appendices.
11	The team includes one alternative representing the status quo to provide a basis of comparison among alternatives.	The team considered a baseline alternative that would have maintained the status quo of Supplemental Low Activity Waste (SLAW) with vitrification as the waste form.
12	The team screens the list of alternatives before proceeding, eliminates those that are not viable, and documents the reasons for eliminating any alternatives.	The team followed a screening process to eliminate some of the initial alternatives identified. The specific scoring methodology used for the screening process was identified to be applied to each technology. This screening was performed by the full FFRDC team in May 2018.
13	The team develops a life-cycle cost estimate for each alternative, including all costs from inception of the project through design, development, deployment, operation, maintenance and retirement.	The team developed full life-cycle cost estimates for each alternative, using existing data and making appropriate adjustments to levelize estimates with consistent dollars that were used for comparison purposes among the alternatives, including retirement of the facilities.
14	The team presents the life-cycle cost estimate for each alternative as a range or with a confidence interval, and not solely as a point estimate.	The team included cost estimates for each alternative that were listed with an accuracy range of <u>-50% to + 100%</u> .
15	The team expresses the life-cycle cost estimate in present value terms and explains why it chose the specific discount rate used.	The team presented life cycle costs in present value terms.
16	The team uses a standard process to quantify the benefits/effectiveness of each alternative and documents this process.	The team presented benefits and effectiveness of each alternative in a table format for ease of review.
17	The team quantifies the benefits/effectiveness resulting from each alternative over that alternative's full life cycle, if possible.	The team quantified the benefits and effectiveness of each alternative of the alternative full life cycle, based on available information in a table format.

18	The team explains how each measure of benefit/effectiveness supports the mission need.	Each measure of the benefit and effectiveness was document in table format for each alternative with some of these measures being qualitative.
19	The team identifies and documents the significant risks and mitigation strategies for each alternative.	The team developed a risk matrix for each alternative and briefly described the mitigation strategies for each risk. This was reviewed by the full FFRDC team in October 1028.
20	The team tests and documents the sensitivity of both the cost and benefit/effectiveness estimates for each alternative to risks and changes in key assumptions.	The team developed as part of the risk matrix, the sensitivity of both cost and schedule for each alternative to risks and key assumption changes. This was reviewed by the full FFRDC team in October 1028.
Process Included in the Selecting a Preferred Alternative Category		
21	The team or the decision maker defines selection criteria based on the mission need.	The NDAA does not call for a recommendation or preferred alternative.
22	The team or the decision maker weights the selection criteria to reflect the relative importance of each criterion.	The team weighted the selection criteria using a five point scale, with 5 indicating most positive and 1 the least positive criteria to evaluate each option. However, the NDAA does not call for a preferred alternative and the FFRCE team does not provide a recommended or preferred alternative.
23	The team or the decision maker compares alternatives using net present value.	The team used net present value in comparing alternatives.
24	An entity independent of the AOA process reviews the extent to which all best practices have been followed (for certain projects, additional independent reviews may be necessary at earlier stages of the process such as for reviewing the study plan or for reviewing the identification of viable alternatives).	NDAA17 directs the National Academies of Science, Engineering, and Medicine to conduct a review of the LAW analysis concurrent with the FFRDC performance of that analysis.

APPENDIX B. EXPANDED DISCUSSION – VITRIFICATION

B.1 TECHNOLOGY OVERVIEW

Supplemental Low Activity Waste (SLAW) could be treated via vitrification, using an additional vitrification facility that will have similar attributes to the Waste Treatment and Immobilization Plant (WTP) LAW facility. This SLAW facility will receive treated supernate from the WTP Pretreatment facility (PT) and the LAW Pretreatment System (LAWPS).⁴⁹ 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 waste form.⁵⁰ 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 waste form 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.⁵¹ 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.⁵² 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 waste form in the IDF. The concentrate will be recycled to the front end of the SLAW process.

B.2 DESCRIPTIONS OF FLOW SHEETS

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,

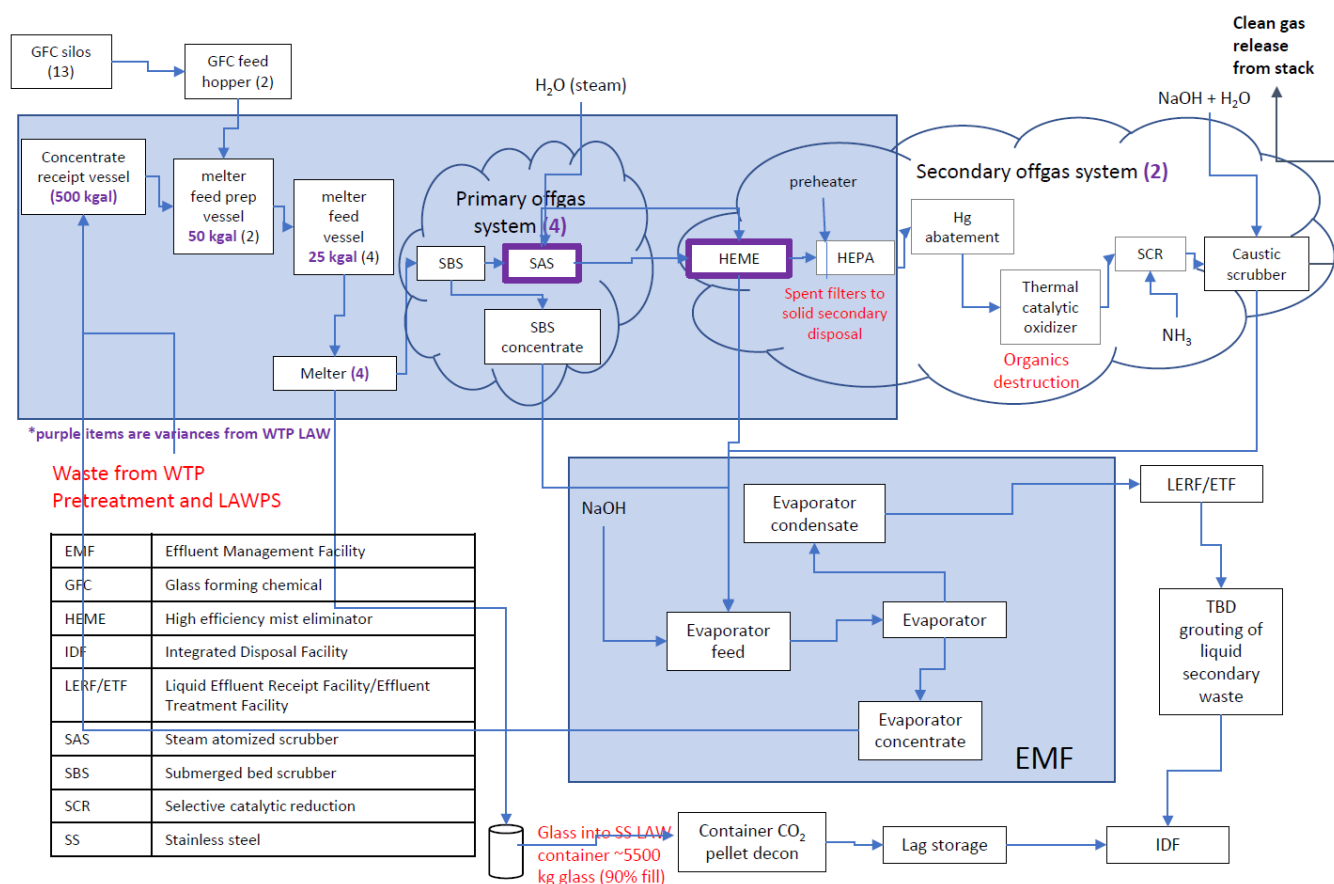
⁴⁹ "LAW Melter Feed Process (LFP) and Concentrate Receipt Process (LCP) System Design Description," Bechtel National Incorporated, River Protection Project, Waste Treatment Plant, Richland, Washington, 2017.

⁵⁰ "System Description for the System LMP, Low Activity Waste Melter," Bechtel National Incorporated, River Protection Project, Waste Treatment Plant, Richland, Washington, 2010.

⁵¹ "LAW Primary Offgas (LOP) and Secondary Offgas/Vessel Vent (LVP) System Design Description," Bechtel National Incorporated, River Protection Project, Waste Treatment Plant, Richland, Washington, 2016.

⁵² "WTP Direct Feed LAW Integrated Processing Strategy Description," Bechtel National Incorporated, River Protection Project, Waste Treatment Plant, Richland, Washington, 2017.

decontamination, and temporary lag storage facility. Each of these unit operations is outlined in the figure below and described in the following subsections.



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^{53,54} to determine the GFC and sucrose additions required for formulation of a compliant glass.⁵⁵ This differs somewhat from the WTP LAW facility, where sampling for compliance will occur in the CRV, though the MFPV will still be sampled.⁵⁶ This sample is considered a process hold point to demonstrate waste compliance.⁵⁷ 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

⁵³ 24590-LAW-RPT-RT-04-0003, Rev 1, Preliminary ILAW Formulation Algorithm Description

⁵⁴ 24590-101-TSA-W000-0009-72-00012, Letter Report – Proposed Approach for Development of LAW Glass Formulation Correlation

⁵⁵ 24590-WTP-PL-RT-03-001, ILAW Product Compliance Plan

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 "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.

design and capability as those of the WTP Balance of Facilities (BOF) glass former handling facility,⁵⁸ but with its scale doubled to support the operation of four melters. The GFCs, their mineral sources,⁵⁹ and acceptable levels of impurities⁶⁰ 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 dusting⁶¹ and fed to the MFPV. Dilution water mass is added to the feed if needed to meet melter feed rheological requirements,⁶² 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.⁶³

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.⁶⁴ 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. Each melter can produce 15 metric tons of glass per day.⁵⁶ The glass must meet melter compatibility requirements including viscosity, electrical conductivity, and liquidus temperature.⁶⁵ These properties are controlled via glass formulation as dictated by the glass property models.^{53,54} In addition to meeting the processing requirements described above, the glass property models are tasked to produce a glass waste form that is compliant with the specifications for disposal, i.e., Product Consistency Text (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

⁵⁸ 24590-LAW-3ZD-LFP-00001, LAW Melter Feed Process (LFP) and Concentrate Receipt Process (LCP) System Design Description

⁵⁹ R.F. Schumacher, "Characterization of HLW and Law Glass Formers," Westinghouse Savannah River Company, Aiken, SC, WSRC-TR-2002-00282, Rev. 1, 2003.

⁶⁰ SCT-MOSRLE60-00-175-01, Final Report - Characterization of HLW and LAW Glass Formers

⁶¹ CCN 077705, Evaluation of Wetting Agents for Glass Former Dusting Control (RTC 170)

⁶² 24590-WTP-RPT-PO-03-007, LAW Melter Feed Rheology Assessment

⁶³ 24590-WTP-RPT-PT-02-005, Rev 8, Flowsheet Bases, Assumptions, and Requirements

⁶⁴ 24590-101-TSA-W000-0010-409-359, LAW Melter System Description

⁶⁵ 24590-LAW-3PS-AE00-T0001, Engineering Specification for Low Activity Waste Melters

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.⁶⁶ Bubbler replacement is expected to be the most frequent maintenance requirement,⁶⁶ with each bubbler having an estimated life span of 26 weeks.^{66,67} Each bubbler has three racks of six bubblers. A rack in each melter is replaced every eight weeks. The melter is not fed during bubbler replacement.

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.⁵⁶ 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.⁵⁶

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.⁶⁸ 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.

⁶⁶ 24590-101-TSA-W000-0010-08-10, Rev 00C, Report – RPP Pilot Melter Bubbler Life Extension Test Results Report

⁶⁷ CCN 103214, Update to the LAW Reliability, Availability, and Maintainability (RAM) Data for the LCP, LFP, LMP, GFR, LOP, and LVP Systems

⁶⁸ 24590-LAW-3YD-LOP-00001, Rev 3

Spent HEPA filters will be transferred to the Central Waste Complex for grouting as Secondary Solid Waste prior to disposal at the IDF.⁶⁹ 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.2.1.4 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 Supplemental LAW, but upgrades are assumed in SP8.

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.⁵⁶ For comparison, the SRS Defense Waste Processing Facility (DWPF) returns 5 gallons of liquid to the tank farm for each gallon of sludge vitrified.⁷⁰ 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.⁵⁶ 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.^{71,72,73,74}

The vitrified waste is poured into the containers, which hold ~6 metric tons (~2,000 gallons feed from the CRV) of vitrified waste.⁵⁶ 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 CO₂ pellet blasting to meet requirements for minimal removable contamination. This system is assumed to be of the same design as that for WTP LAW.^{56,75} The gas and particulate stream is drawn through HEPA filters, and then exhausts to the building ventilation

⁶⁹ "River Protection Project System Plan," ORP-11242, Revision 8, DOE Office of River Protection, Richland, Washington, 2017.

⁷⁰ "DWPF Recycle Evaporator Flowsheet Evaluation (U)," WSRC-TR-2005-00226, Revision 1, Savannah River National Laboratory, Aiken, South Carolina, 2005.

⁷¹ 24590-LAW-3ZD-LRH-00001, Rev 0, LAW Container Receipt Handling (LRH) System Design Description

⁷² 24590-LAW-3ZD-LPH-00001, Rev 0, LAW Container Pour Handling (LPH) System Design Description

⁷³ 24590-LAW-3ZD-LFH-00001, Rev 0, LAW Container Finishing Handling (LFH) System Design Description

⁷⁴ 24590-LAW-3ZD-LEH-00001, Rev 0, LAW Container Export Handling (LEH) System Design Description

⁷⁵ 24590-LAW-M5-V17T-00013, Process Flow Diagram LAW Vitrification Container Decontamination (System CDG)

system. Spent HEPA filters will be transferred to the Central Waste Complex for encapsulation as Secondary Solid Waste prior to disposal at the IDF.⁷⁶ Finished containers are stored until transfer to the IDF.

B.2.2 Alternative Flow Sheets

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 waste form 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 waste form, reduce the burden on the liquid secondary waste processing facilities, and reduce the source term for ILAW in the Hanford IDF.

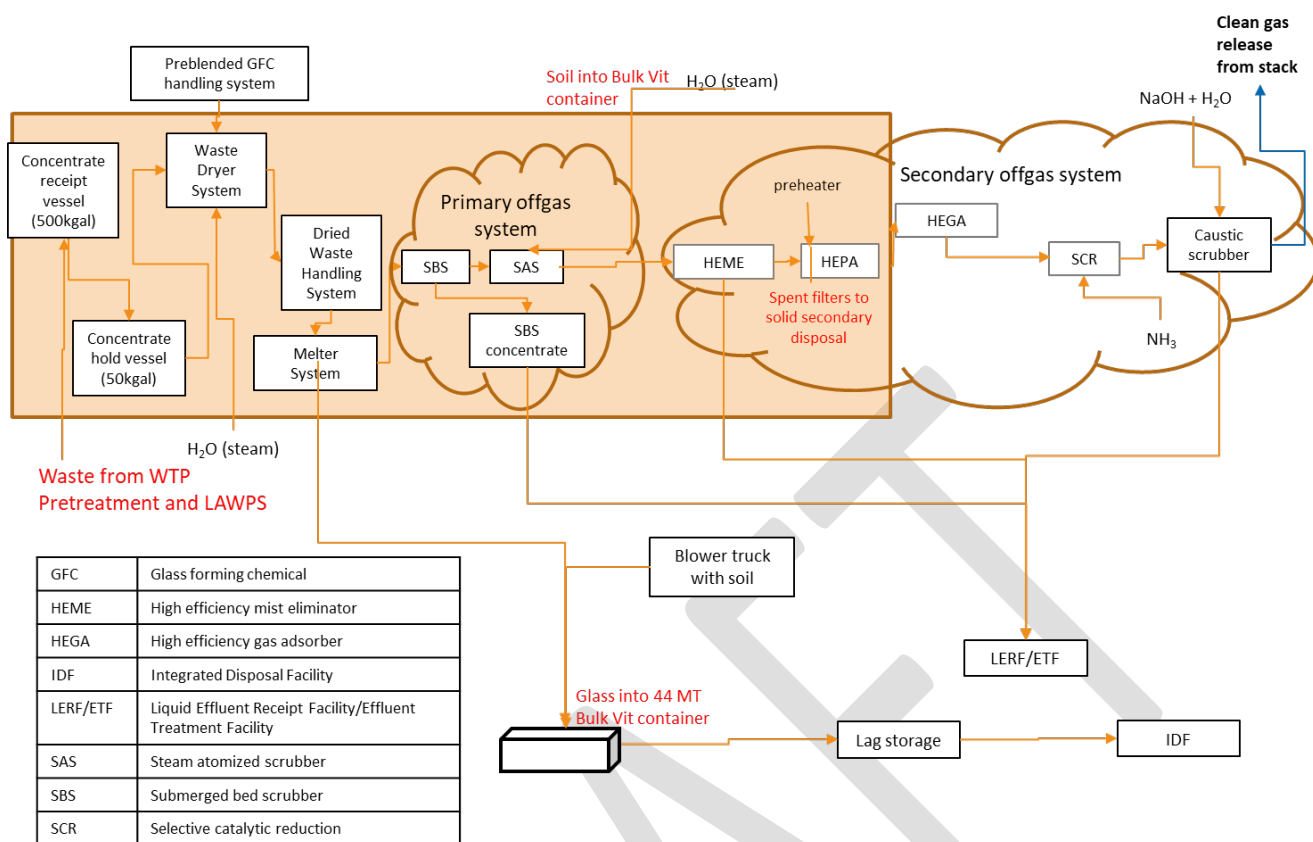
Implementation of the alternative flowsheet will require the design and construction of a facility for immobilizing liquid secondary waste in grout. DOE experience with similar facilities would be leveraged for this purpose. A grout waste form production facility is relatively simple, with four main 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.

B.2.2.2 In Container Vitrification™

For In Container Vitrification (ICV), the SLAW facility will receive treated supernate from WTP PT and LAWPS.⁴⁹ 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.⁷⁷ 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.

⁷⁶ "River Protection Project System Plan," ORP-11242, Revision 8, DOE Office of River Protection, Richland, Washington, 2017.

⁷⁷ "Bulk Vitrification Technology for the Treatment and Immobilization of Low-Activity Waste," RPP-48703, Revision 0, Washington River Protection Solutions, Richland, Washington, 2011.



B.2.2.3 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.

B.2.2.4 Melters

Dried melter feed is gravity fed to the pre-staged melt container. The melt container is a 7.5-ft (tall) x 7.5-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.⁵⁶ 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.⁵⁶

The offgas generated from each of the melter 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.⁷⁸ 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.⁷⁹ 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 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 Supplemental LAW, 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.⁵⁶ For comparison, the SRS Defense Waste Processing Facility (DWPF) returns 5 gallons of liquid to the tank farm for each gallon of sludge vitrified.⁸⁰ Therefore, there is a risk

⁷⁸ 24590-LAW-3YD-LOP-00001, Rev 3

⁷⁹ "River Protection Project System Plan," ORP-11242, Revision 8, DOE Office of River Protection, Richland, Washington, 2017.

⁸⁰ "DWPF Recycle Evaporator Flowsheet Evaluation (U)," WSRC-TR-2005-00226, Revision 1, Savannah River National Laboratory, Aiken, South Carolina, 2005.

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.^{81,82,83,84}

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.⁸⁵ Finished containers are stored until transfer to the IDF.

B.3 ASSUMPTIONS

The following assumptions are made regarding the baseline vitrification flow sheet:

- 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.

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 waste form with the secondary waste
- Approvals can be obtained for transportation and offsite disposal of secondary waste immobilized in grout

B.4 RISKS

Risks associated with the baseline vitrification flow sheet 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

⁸¹ 24590-LAW-3ZD-LRH-00001, Rev 0, LAW Container Receipt Handling (LRH) System Design Description

⁸² 24590-LAW-3ZD-LPH-00001, Rev 0, LAW Container Pour Handling (LPH) System Design Description

⁸³ 24590-LAW-3ZD-LFH-00001, Rev 0, LAW Container Finishing Handling (LFH) System Design Description

⁸⁴ 24590-LAW-3ZD-LEH-00001, Rev 0, LAW Container Export Handling (LEH) System Design Description

⁸⁵ CH2M-36501-FP, Rev 0, Design of the Demonstration Bulk Vitrification System for the Supplemental Treatment of Low Activity Tank Waste at Hanford

- 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 waste form
- Approval is not obtained for offsite transportation of secondary waste immobilized in grout
- An offsite disposal facility is no longer available

B.5 BENEFITS AND COST ESTIMATE (PROJECT AND LIFECYCLE)

B.6 SCHEDULE

B.7 REGULATORY COMPLIANCE (PROCESS, TRANSPORT, DISPOSAL/WASTE FORM)

B.8 OBSTACLES

TBD

APPENDIX C. EXPANDED DISCUSSION – STEAM REFORMING

C.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 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 (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 waste form. The IWTU produces a quite water-soluble sodium carbonate-based solid granular product that is not a durable, leach-resistant waste form. In the case of Hanford SLAW treatment, the goal indeed is to produce a durable, leach-resistant waste form, which FBSR has been shown to achieve using the needed design and operation.

C.1.1 Durable, Leach-Resistant Mineralized Na-Al-Si Waste Form

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 waste form 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 waste form is the intended waste form for FBSR treatment of Hanford SLAW.

C.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 waste form that can be produced from the Hanford SLAW.

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

C.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°C.

The fluidized bed is maintained at nominally 725-750°C by preheating the incoming fluidizing steam to about 600°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 H₂ and other reduced gas species such as CO and CH₄ that react with the nitrates in the waste feed (WF), converting the nitrates and nitrites to N₂ and H₂O. The coal and O₂ 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 H₂, CO, and hydrocarbon gas species in the DMR outlet gas.

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 waste form. 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 N₂ 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°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 N₂, CO, CO₂, hydrocarbon gases, and H₂O.

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 H₂ 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% H₂O; 10-15 vol% CO₂; 10-15 vol% N₂; 1-3 vol% H₂; 1 vol% CO; 0.5-1 vol% NO_x; <0.1 vol% hydrocarbons; and <100 ppmv other gas species such as SO₂ 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 waste form. 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).

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

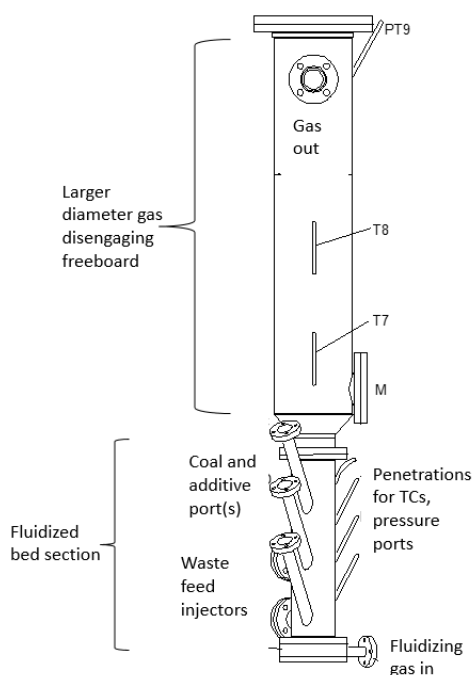


Figure C-1. Illustration of a fluidized DMR vessel (from Olson 2004a).

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.

C.2.2 How Fluidized Bed Steam Reforming Would Treat Hanford Supplemental LAW

The Supplemental LAW treatment system feed vector varies widely and presents flowrate and composition challenges for the SLAW treatment process. Table C-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 C-1. Supplemental LAW 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.			

C.3 FBSR PROCESS OPTIONS AND DIAGRAMS

Three FBSR options are proposed, based on the desired waste form. Steam Reforming Case 1 (Figure C-3), provides a durable, mineralized waste form 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 C-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 C-5) features disposal of the granular waste form 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.

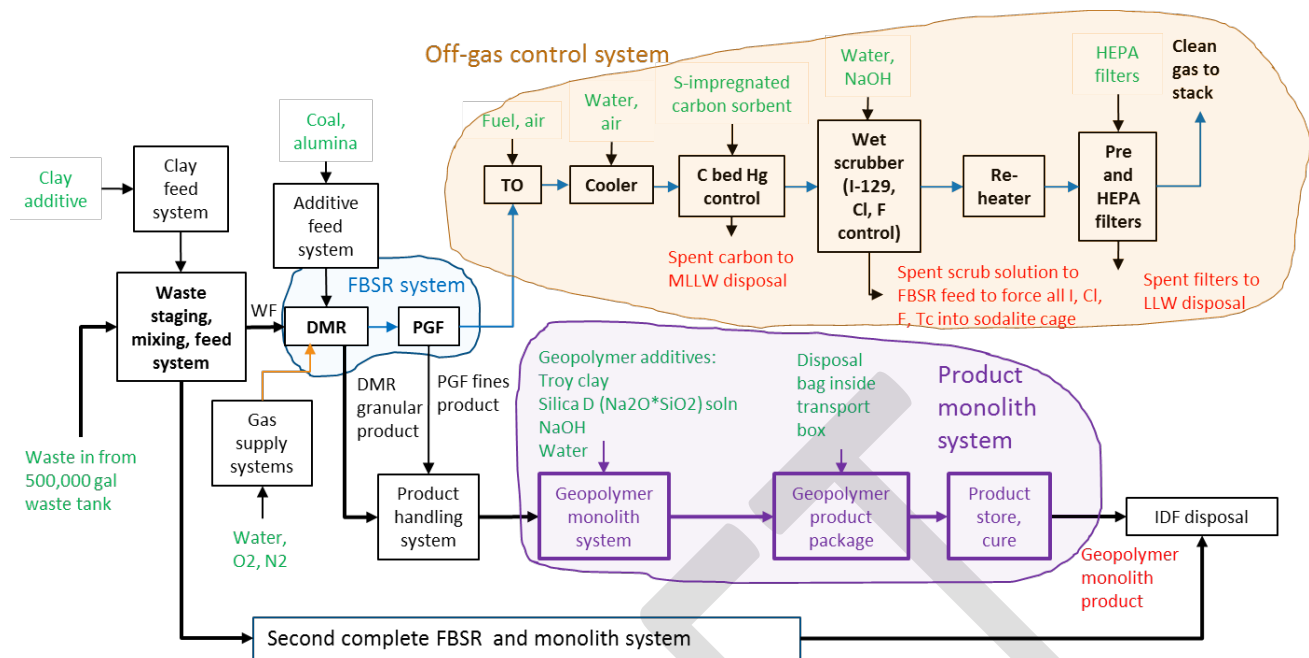


Figure C-2. Case 1 Mineralizing FBSR to IDF; solid monolith product disposed at IDF (secondary wastes also disposed at IDF)

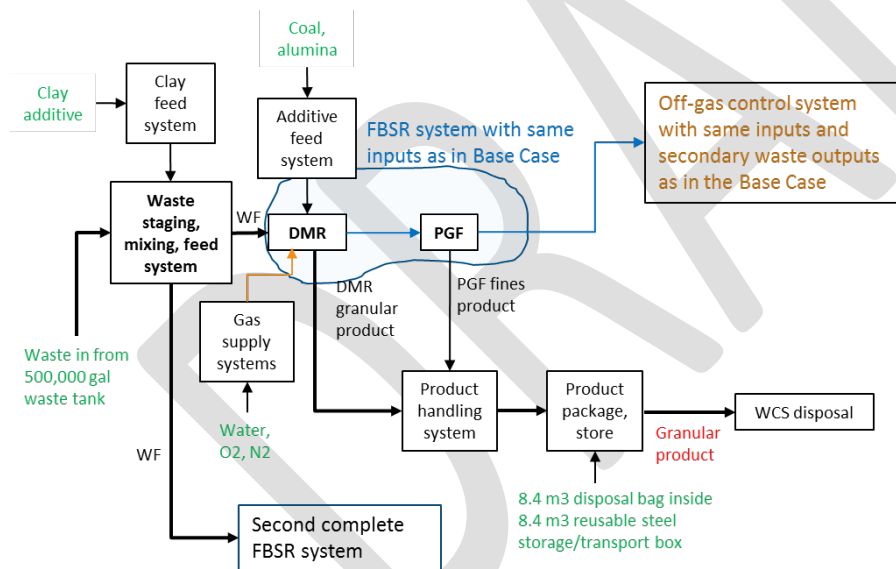


Figure C-3. Case 2, Mineralizing FBSR to WCS; granular solid product disposed at WCF (secondary wastes also disposed at WCF)

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.

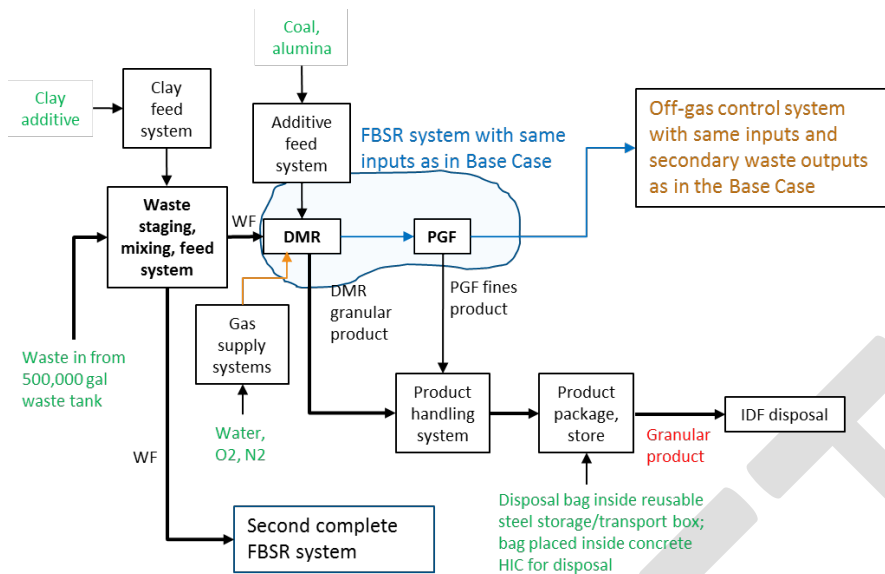


Figure C-4. Alternative Treatment Option 3c, Steam Reforming to WCS: Two DMR systems; granular solid product disposed at IDF inside concrete HICs (secondary wastes also disposed at IDF).

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.

C.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 $\sim 100 \text{ ft}^3$. 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.

C.3.2 FBSR Waste Feed System

Figure C-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.

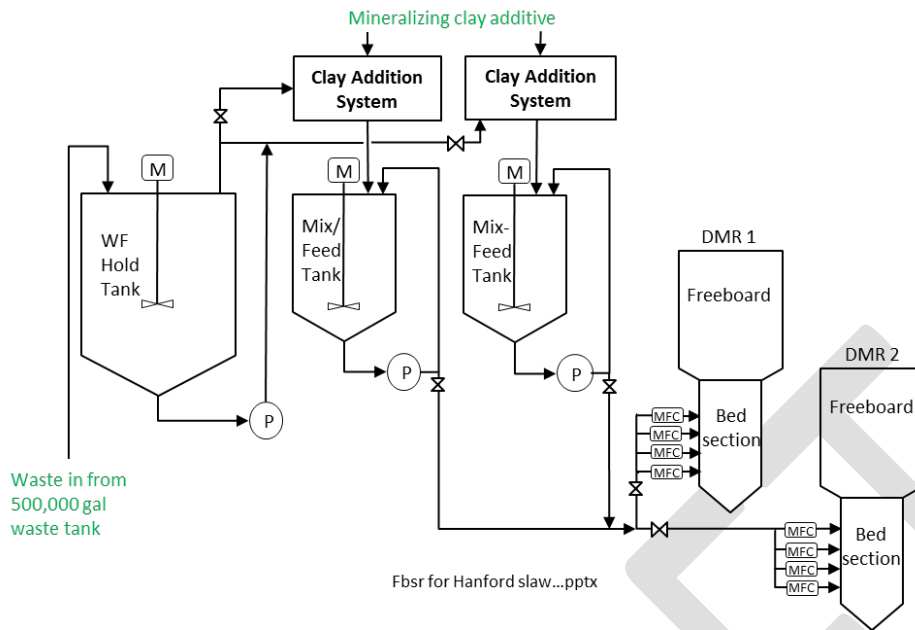


Figure C-5. Conceptual FBSR WF system

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 C-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.

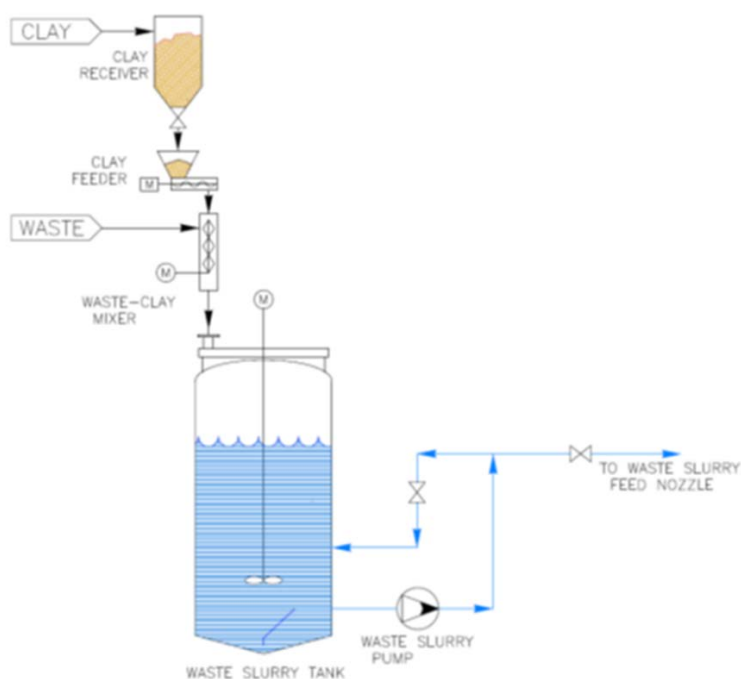


Figure C-6. Clay and waste high shear in-line mixing system concept design.

C.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 Supplemental LAW 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 waste form 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 CO₂, H₂O, H₂, CO, gasified hydrocarbons, mainly CH₄, and SO_x. Most (about 90%) of the reacted coal is converted to CO₂ and H₂O; about 10% is converted to H₂, 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 C-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.

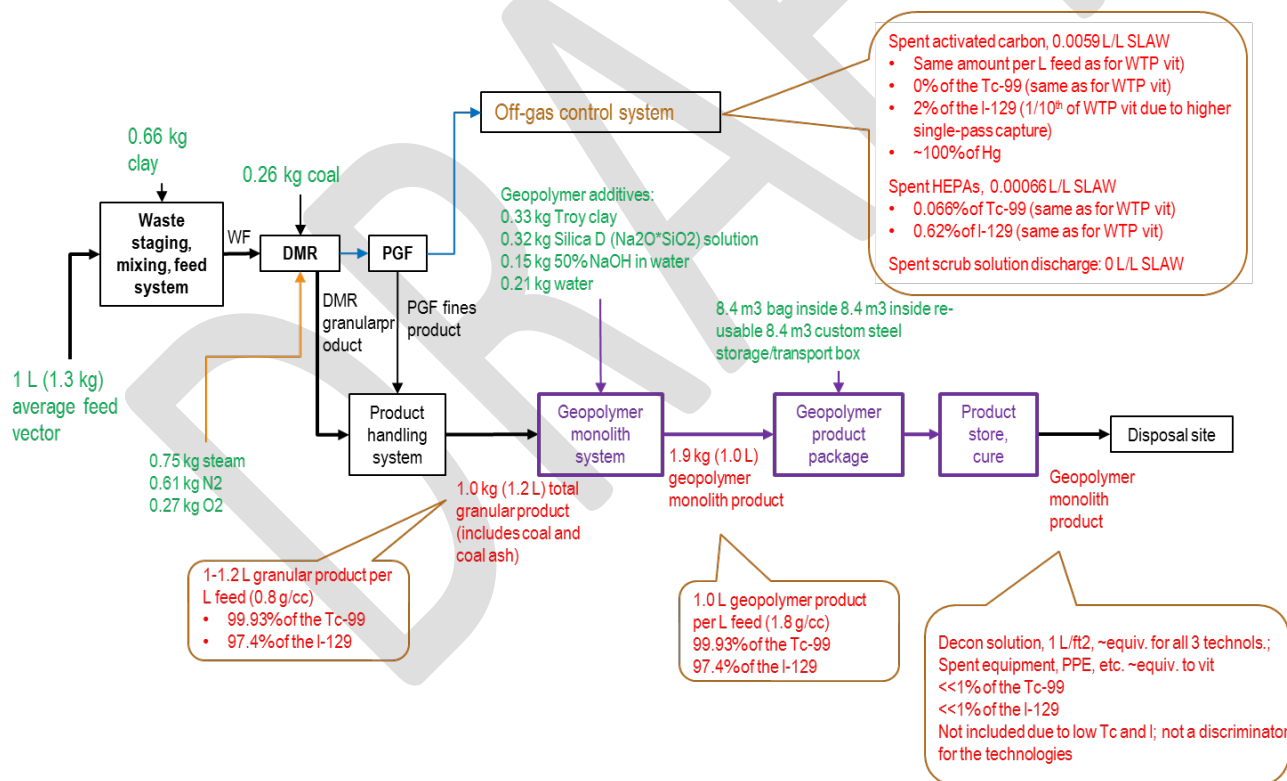


Figure C-8 Initial mass balance results for FBSR treatment of Hanford SLAW.

C.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 C-2 and C-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 waste form.

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

Table C-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 C-3. Air emissions compliance.

	Mitigations in addition to engineering
Radionuclides	Multiple redundant filters and scrubbing, HEPA's
NOx and Hazardous/toxic organics	Steam reforming chemistry, kinetics, mass & heat transfer
Hazardous/toxic particulate, metals	Multiple redundant filters and scrubbing, HEPA's
Hazardous/toxic acid gases	Multiple dry and wet scrubbing

C.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 C-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 already demonstrated in the Erwin ResinSolutions Facility and in the IWTU. These are generally rated at high TRL.

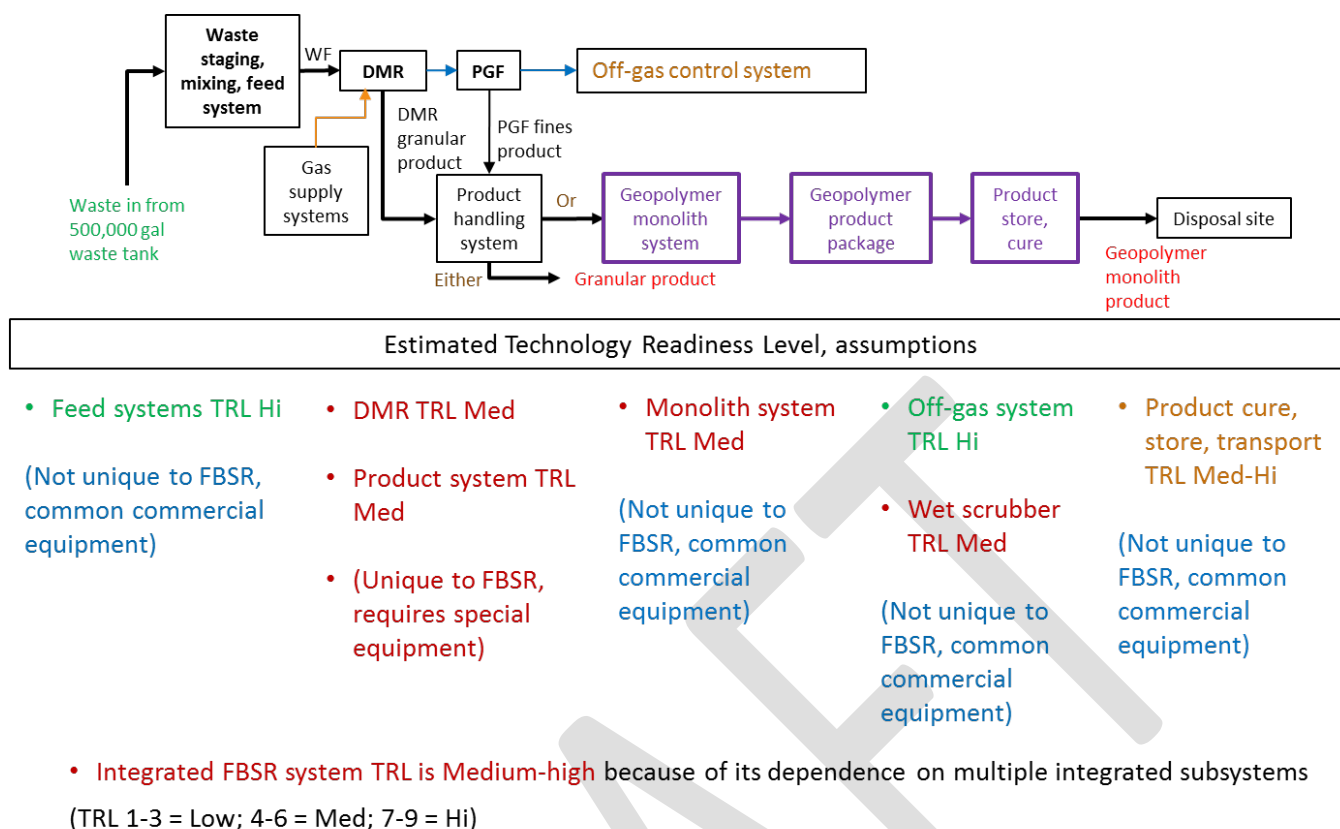


Figure C-8 Rough maturity level estimates for the FBSR processing system.

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 ResinSolutions 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 ResinSolutions 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 its 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 troubleshooting 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 ResinSolutions Facility and the IWTU because of the goal to produce the durable mineral waste form 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.

C.7 COST AND SCHEDULE

The IWTU and the Erwin ResinSolutions 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 ResinSolutions 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 Table C-4. The 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 (2018) is 13 years, although six 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 C-4. Estimated costs for the FBSR Cases 1 and 2.

Tech Dev	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replace	D&D	Total Program Cost
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Case 1 - IDF								
\$480M – \$1,100M	\$1,000M – \$2,600M	\$1,900M – \$4,400M	\$1M – \$2.6M	\$3,300M – \$4,900M	N/A	\$300M – \$690M	\$TBD	\$8,500M – \$15,000M
Case 2 - WCS								
\$480M – \$1,100M	\$1,000M – \$2,600M	\$1,900M – \$6,900M	N/A	\$2,500M – \$3,800M	\$1,900M – \$2,800M	\$300M – \$690M	\$TBD	\$9,500M – \$19,000M

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.

C.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 waste form would not be equal to that of the WTP glass...” This and other conclusions about non-glass waste forms and steam reformed waste forms was based on data available at that time. Other documents contemporaneous to the 2012 EIS drew different conclusions. The National Research Council “Waste Forms Technology and Performance, Final Report,” (NRC 2011) concludes “...crystalline ceramic waste forms produced by fluidized bed steam reforming have good radionuclide retention properties and waste loadings comparable to, or greater than, borosilicate glass. This waste form 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 waste form 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 waste form 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).

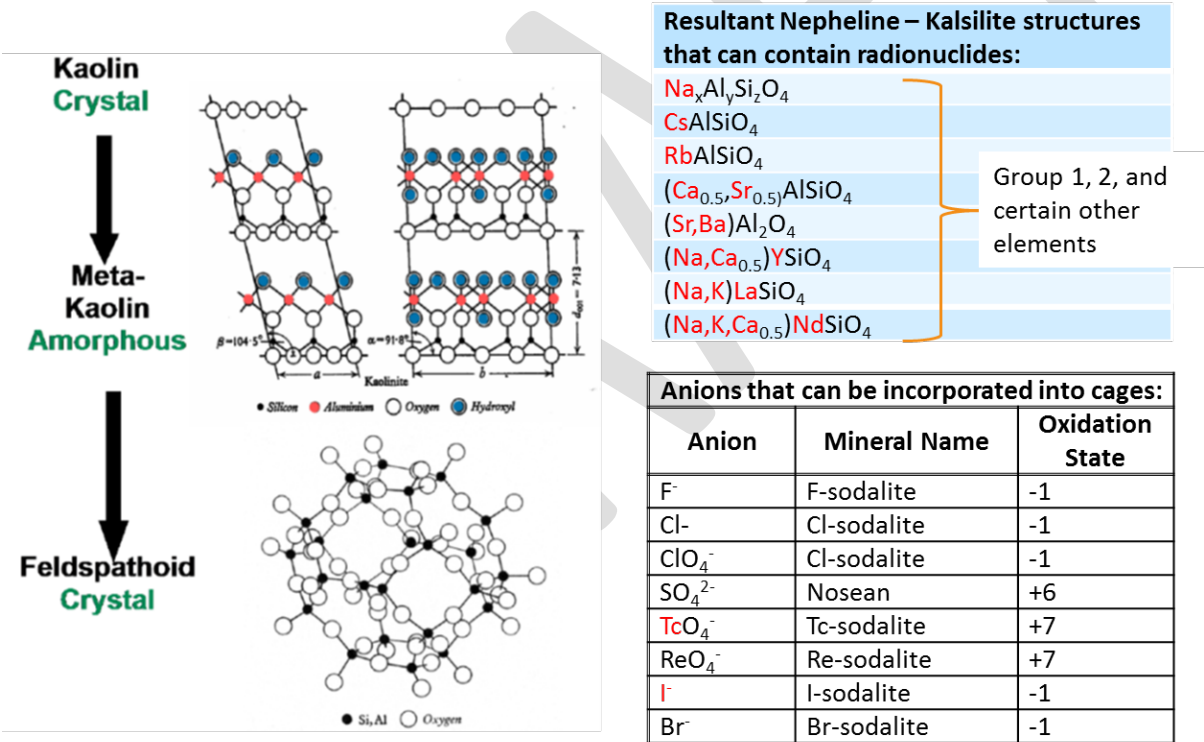
At least two issues remain. Permitting of non-glass waste forms in the IDF have not been done. First, and prior to and during the course of this study, most local and state level stakeholders have expressed strong opinions against non-glass waste forms for the SLAW. Second, many of these stakeholders have referred to, or used, the phrase “good as glass” when describing the candidate waste forms. Some scientists and stakeholders have different opinions about how waste form performance tests should be applied to non-glass waste forms. For example, while NRC 2011 recommends some performance tests for non-glass waste forms, Schepens 2003 states that some of those same performance tests are not suitable for non-glass waste forms. This issue may

need additional investigation and resolution to provide a more widely accepted basis for demonstrating the performance of non-glass waste forms. This type of resolution, together with IDF performance assessments for non-glass waste forms, may be needed to obtain more acceptance of non-glass waste forms for the SLAW.

C.8.1 The Mineralizing Process

The mineralizing process begins with the kaolin clay (Al₂Si₂O₅(OH)₄) added to the WF. The clay particles dehydrate as the OH is lost when heated above 550°C in the DMR (Figure C-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 (NaAlSiO₄ with hexagonal symmetry) and carnegieite (nominally NaAlSiO₄ 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 include:

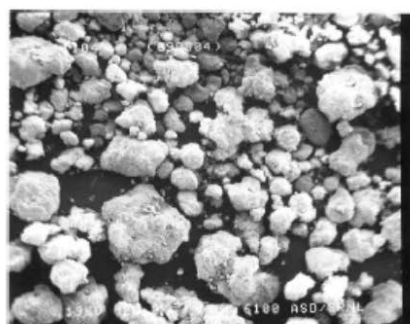
- Nepheline (nominally NaAlSiO₄).
- Sodalite (nominally M₈(Al₆Si₆O₂₄)X₂, where M is an alkali cation such as Cs, K, Na, etc. and X is a monovalent anion or a monovalent or divalent oxyanion, such as Br⁻, Cl⁻, I⁻, TcO₄⁻, ReO₄⁻, SO₄²⁻, etc.).
- Nosean (nominally Na₈[AlSiO₄]₆SO₄ with a larger cubic sodalite structure).
- Carnegieite (nominally NaAlSiO₄ of orthorhombic symmetry).



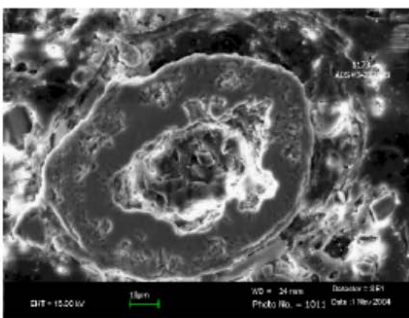
C.8.2 Granular and Monolith Mineral Waste Forms

Figure C-10 shows scanning electron micrographs of the granular mineralized waste form. 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.

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

C.8.3 Waste Form 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 $\text{Na}_2\text{O} - \text{Al}_2\text{O}_3 - \text{SiO}_2$ 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 $\text{Na}_2\text{O} - \text{Al}_2\text{O}_3 - \text{SiO}_2$ stoichiometry similar to the target stoichiometry for the monoliths.

C.8.4 Product Analyses and Durability Tests

With respect to waste forms and waste form tests, NRC 2011 findings include:

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

In accordance with the recommendations from NRC 2011, the following durability tests were used for both the granular and monolith waste forms 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 waste form 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 C-5 summarizes the performance tests by many different researchers at PNNL, ORNL, SRNL, and WRPS to demonstrate if the mineralized waste form 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 waste forms 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 waste form 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 cage; the remainder is in a +4 state in TcO_2 or $\text{Tc}_2\text{S}(\text{S}_3)_2$; 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).
- $<2 \text{ g/m}^2$ 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 $\sim 10^{-3} \text{ g}/(\text{m}^2\text{d})$.
- Re release was similar to both I and Tc release in this waste form.
- 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 $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ (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 $[(2.1 \pm 0.3) \times 10^{-2} \text{ g}/(\text{m}^2\text{d})]$ 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 $< 2 \text{ g}/\text{m}^2$) 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 $> 500 \text{ psi}$ but clay based monoliths performed better than fly ash based geopolymers.

Table C-5. Summary of FBSR mineralized waste form 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			
SAIC/STAR 7/03 Soelberg 2004a, Marshall 2003	SBW	Pariezs 2005, Jantzen 2006a, 2006b		None	Jantzen 2013	Fines	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.											

C.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 C-6. 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 waste form. 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 C-6. 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 waste form. 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 C-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 C-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.

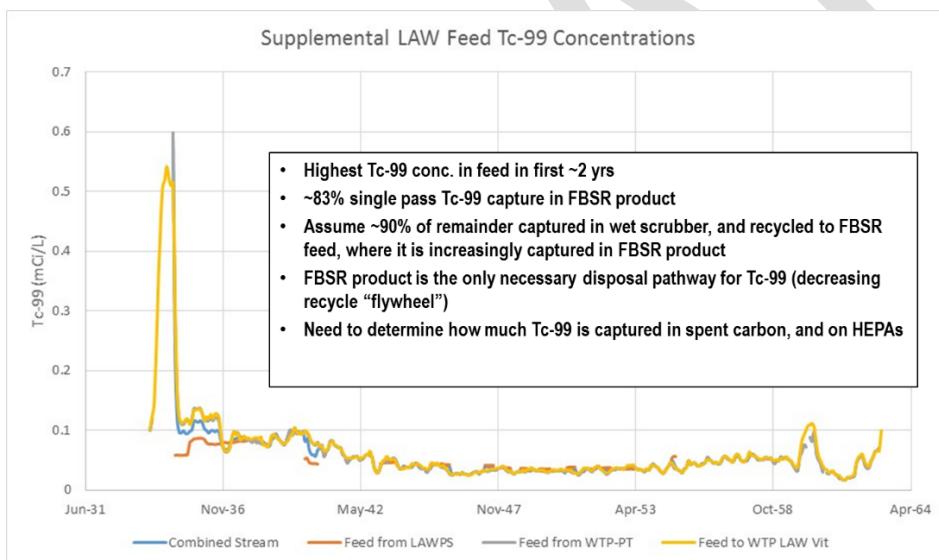


Figure C-12 Control and disposal of Tc-99 in the FBSR process.

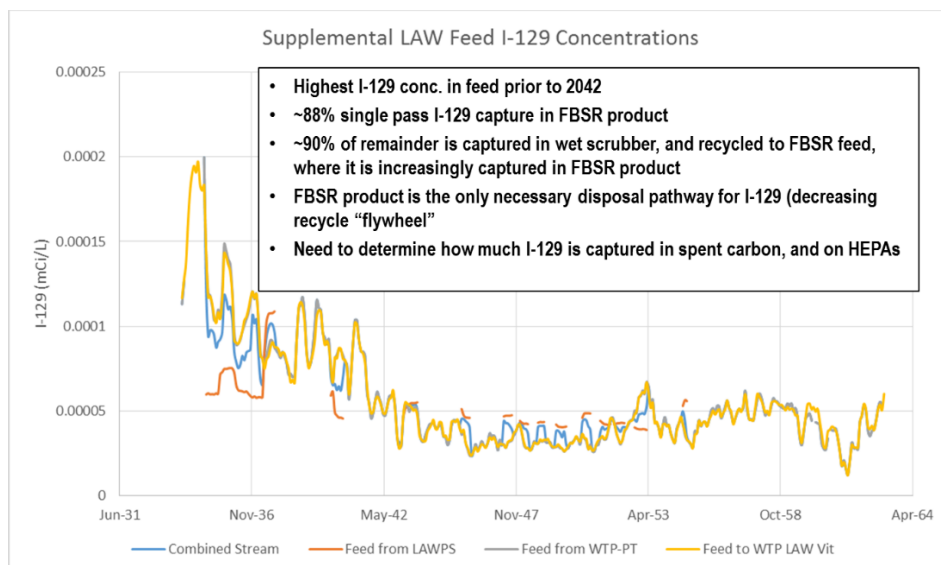


Figure C-13 Control and disposal of I-129 in the FBSR process.

C.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 waste form performance to enable stakeholders to consider if the mineralized waste form 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 C-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 C-7.

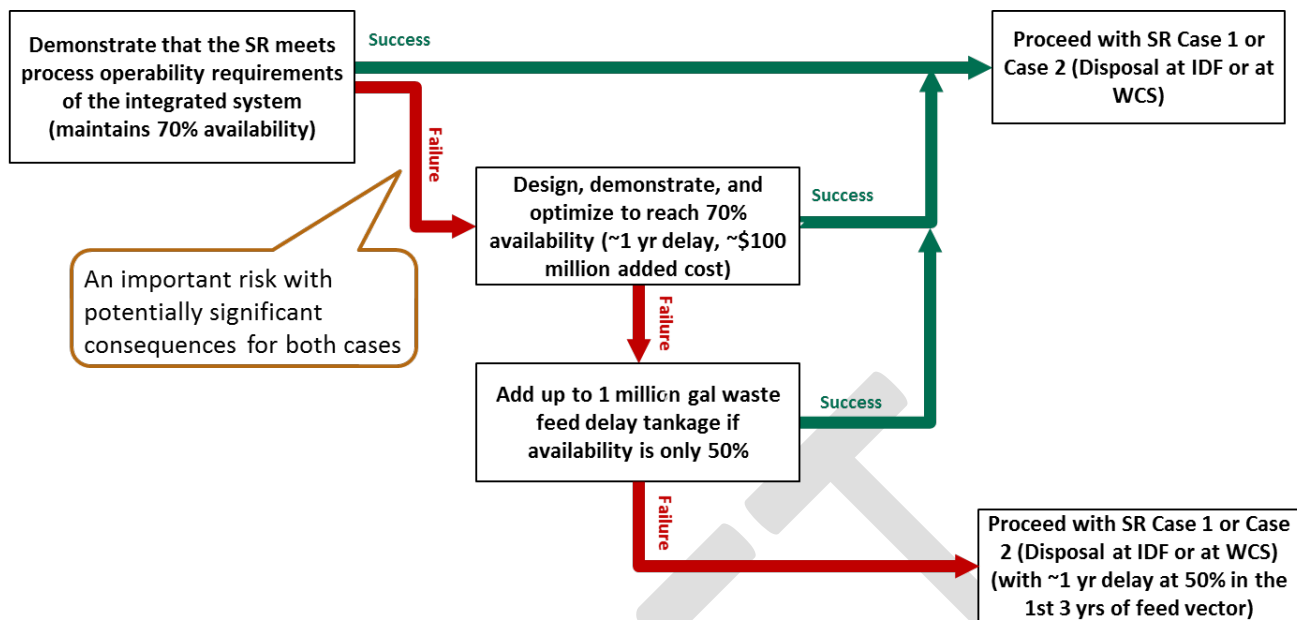


Figure C-14. FBSR operability risk and mitigations.

Table C-7. Other FBSR risks and mitigations.

Risks	Potential mitigations
1. Case 1, IDF: During demonstration testing, waste form fails to meet IDF performance requirements.	i. Modify additives and stoichiometries. ii. Proceed with Case 2 (Disposal at WCS).
2. Case 1, IDF: Partitioning of Tc99 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 waste forms. 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.

C.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 ResinSolutions 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 C-8.

Table C-8 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 "sandcasting" between 2016-2018 to present.

Resolutions: "Sandcasting" 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 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, if the study determines that the pressure drop is caused by corrosion of the Inconel 625 filters. Options being evaluated include changing the filter media, anti-corrosion coatings, and operating at lower PGF temperatures to reduce corrosion.

C.9.1.1 Underlying Issues

The startup challenges from 2012-2016 have been reviewed by Fluor Idaho, DOE-Idaho, and DOE Headquarters, and reported to the National Academy of Sciences as follows (Thompson 2018):

- “The chemical reactions and hydrodynamic processes in the DMR are complex and intertwined.
 - There was insufficient technology maturation testing, modeling and engineering assessments to adequately underpin the project. Chemistry, kinetics, and fluidization were not adequately understood and assessed, and modeling tools were not developed and utilized.
 - Insufficient technology maturation activities led to insufficient expertise and experience with this process which impacted the design and operational approach.
 - Risks of first-of-a-kind systems were not recognized. The lack of understanding (a) led to various flaws in the design, specifications, and operational procedures, and (b) contributed to mis-diagnosing testing outcomes which substantially lengthened the start-up and commissioning phase.
 - Optimistic assumptions impacted the project approach relative to plant operability and reliability. Throughput assumptions and mission duration estimates drove poor decisions on preventative maintenance, spare parts, and redundancy.
 - Several RadCon related controls and first-of-a-kind systems were not well thought out or not sufficiently developed/matured. Examples include the canister fill system, sampling system, and vessel decontamination approach.”

C.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.

C.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 BDAT requirements similar to vitrification. The process can efficiently destroy hazardous organics, nitrates and NO_x, and ammonium compounds.
- Waste form benefits: According to recent waste tests, steam reforming can produce a durable waste form. 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.

C.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 C-9). 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 waste form with a ~2-100x lower-volume, durable mineralized waste form. 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 waste form would be the amounts of undissolved and dissolved inorganic solids, that would be converted into the durable mineral waste form.
- 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 C-9 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%

C.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 waste forms.

- Develop consensus on how to assess performance of non-glass waste forms.
- Update conclusions of the 2012 TC and WM EIS to account for new steam reforming waste form 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 waste forms 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.

C.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 ResinSolutions 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 waste form.
- Retain radionuclides, halogens, and hazardous metals with efficiencies high enough to be the waste form 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 waste form.

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 D. EXPANDED DISCUSSION – GROUT

D.1 TECHNOLOGY OVERVIEW

D.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 waste forms. Grout technology has a long history of being used to transform radioactive aqueous liquid and sludge waste streams into solid waste forms 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 radioactive particulate waste and debris encapsulation. 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 [IAEA, 2018 in press].

Grout technology can be tailored for a range of waste chemistries, available cement ingredients, and process, and final waste form 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 diffusion barrier 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 waste forms have good thermal, chemical and physical stability
- Alkaline chemistry of grout waste forms 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 waste form 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 waste form 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 waste form 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).

D.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 (2005) 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, 2005; 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; 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 and, hence, have not been tested with LAW.

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.

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 D.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 an neutral-pH ammonium sulfate solution whereas the LAW feed vector is a sodium-nitrate, sodium-hydroxide solution with typically high pH. These alternative formulations and waste streams could result in compositions and microstructures of the hydrated grout that differ from those found in Cast Stone formulations combined with LAW.

D.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). 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). 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.

D.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 waste form would perform sufficiently well with respect to retaining anionic species of radionuclides (particularly oxidized forms of technetium and iodine), which are assumed to reside primarily in the aqueous pore fluids and/or sorbed to solids in contact with the pore fluids as opposed to within the solids formed during the hydration of the grout. 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 phases other than pore fluid would significantly increase retention of Tc/I within the grouted waste form. The assessment below assumes the Tc/I are present in pore fluids and released by diffusion; hence, it is conservative.

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., ⁹⁹Tc release predicted by Mann, et al., 2003). However, recent studies have suggested that some grout 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). This section reviews the current understanding of grouted waste forms and retention of technetium and iodine.

Release of technetium and iodine from grouted waste forms has generally been modeled as a diffusion-controlled release process often coupled with an advective transport process. In this approach, release rates are largely a function of (1) the concentration gradient from the grouted monolith to the adjacent pore water and (2) a diffusion coefficient that is a function of the diffusing species and of the material properties of the grouted monolith. In the performance assessment for the IDF, grouted secondary wastes are modeled with an advective-diffusive flow, recognizing an effective diffusion coefficient and an apparent diffusion coefficient (DOE, 2017). The effective diffusion coefficient accounts for the impact on a free-water diffusion coefficient due to various physical factors (tortuosity, porosity, saturation). The apparent diffusion coefficient additionally accounts for some chemical retardation factors through the use of a distribution coefficient for the partitioning between the pore fluid and the grout solid; the net effect is that a high distribution coefficient results in a lower apparent diffusion coefficient and, hence, a lower release rate.

The diffusion coefficients for Tc and I have typically been determined by short term experimental methods—e.g., ANSI/ANS 16.1 (2003) or EPA 1315 (EPA, 2013); see Serne, et al. (2016) for a detailed description of experimental methods and a discussion of various types of diffusion coefficients. 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.

The variation in measured diffusion coefficients for technetium is illustrated in Figure D-1, with the details on the various studies summarized in Table D-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 D-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	$7.7.0 \times 10^{-9}$ (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} ($0.8\text{--}6.3 \times 10^{-10}$)	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 D-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

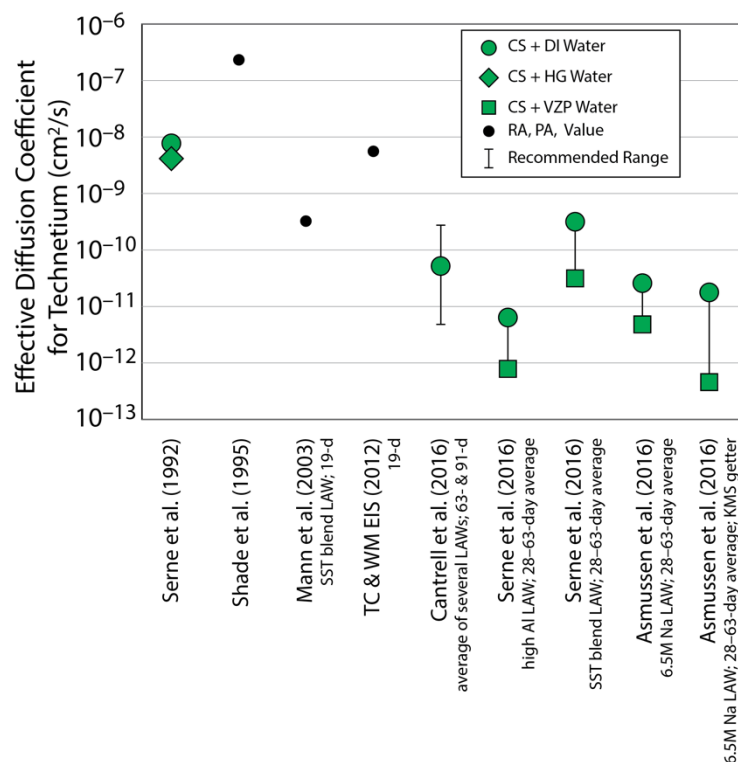


Figure D-1. Plot of effective diffusion coefficients for technetium in various grout-based waste forms made from low-activity wastes. Additional details for each of the studies shown are provided in Table D-1.

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 due to the formation of Tc-bearing solids (i.e., release is solubility limited). 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 waste form, the microstructure of the waste form, 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 waste form, 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, we have generally 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 may 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. D-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.
- *Use of “getters” for technetium and/or iodine*—Recent studies (e.g., Qafoku et al., 2014; Asmussen, et al., 2018) have shown potential for the use of special compounds that can bind Tc or I. These compounds can be used in combination with the Cast-Stone process to improve retention characteristics.

Figure D-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). Several observations emerge from Figs. D-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.

Figure D-3 shows the same trends for effective diffusion coefficients for iodine, also using data reported in Westsik et al. (2013a). Observations generally parallel those for technetium, except that for iodine the spread in effective diffusion coefficients is less (only about an order or magnitude). As can be seen in Fig. D-4, iodine behaves comparable to nitrate, which is generally believed to be unaffected by chemical retardation processes in these systems.

In summary, effective diffusion coefficients for technetium based on recent studies suggest values 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. However, these 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 waste form performance in IDF. (Documenting waste-form performance for grouted SLAW is not necessary for disposal at WCS.). The available data on iodine are more limited (Table D-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).

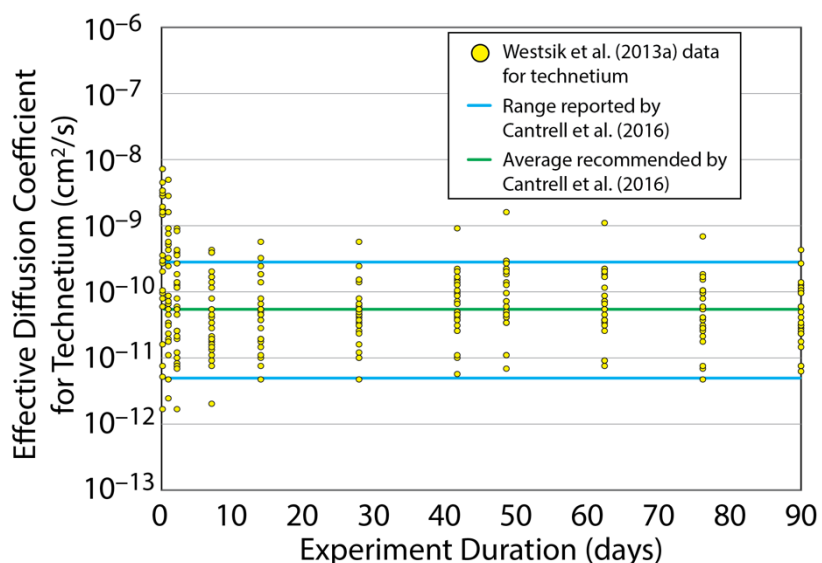


Figure D-2. Plot of effective diffusion coefficients for different durations of the experiment. Data show effective diffusion coefficients for technetium based on data in Westsik et al. (2013a), which were used by Cantrell et al. (2016) in developing recommended values for the Tc diffusion coefficient.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

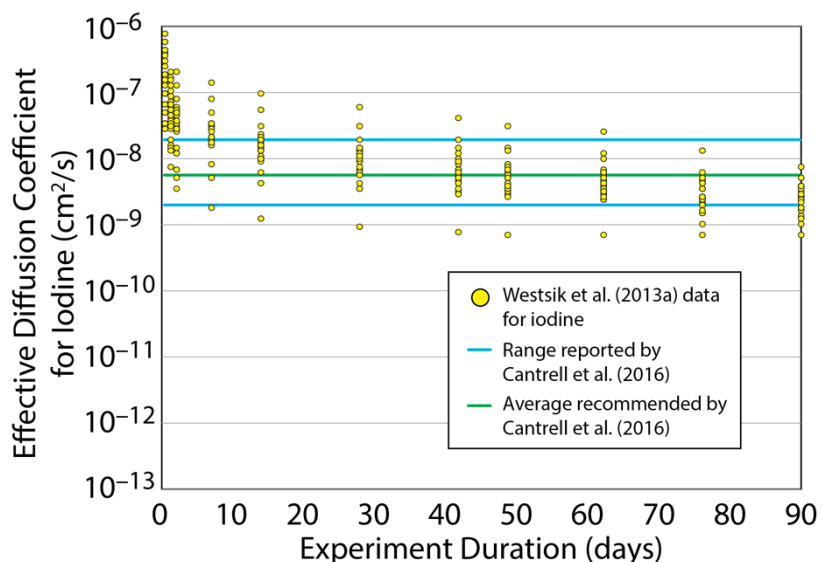


Figure D-3. Plot of effective diffusion coefficients for iodine for different durations of the experiment. Data show effective diffusion are based on data in Westsik et al. (2013a), which were used by Cantrell et al. (2016) in developing recommended values for the I diffusion coefficient. The green line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

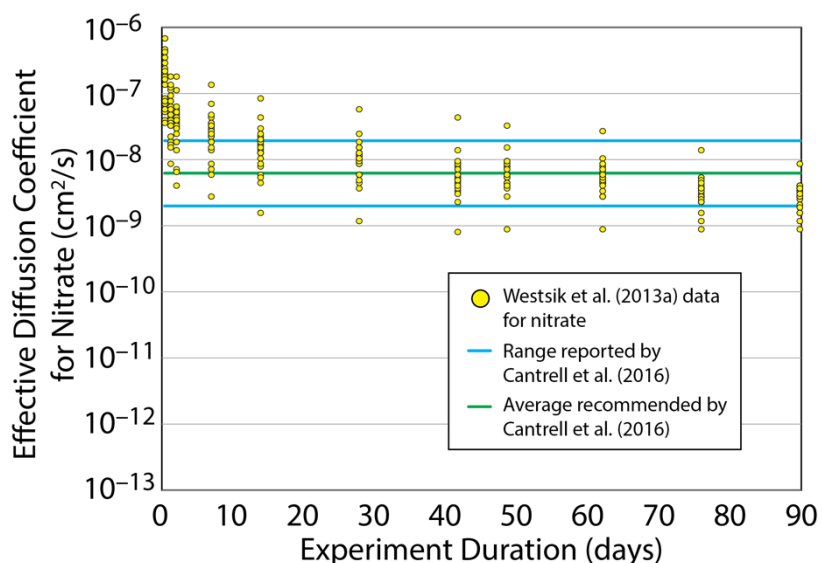


Figure D-4. Plot of effective diffusion coefficients for nitrate for different durations of the experiment. Data show effective diffusion are based on data in Westsik et al. (2013a), which were used by Cantrell et al. (2016) in developing recommended values for the I diffusion coefficient. The green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

D.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 waste form (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 waste form 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 D.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 waste form. 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.

D.2.1 Grout Case I (Disposal at IDF)

The grout case I process flow diagram considered in this assessment is shown in Figure D-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, 2005). 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-m³ 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-m³ size is compliant with disposal at WCS, which is considered in grout case II in Section D.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 D.1.4, the technical maturity of grout-based formulations relative to waste form 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 waste form performance at the IDF.

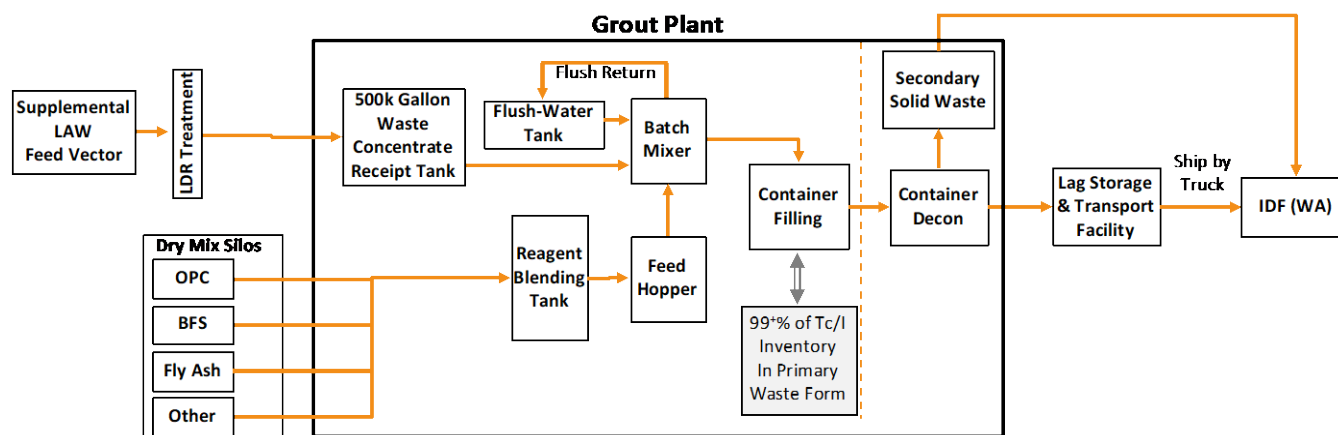


Figure D-5. Process flow diagram for grout case I, where the final Cast-Stone monoliths are disposed of at the Integrated Disposal Facility (IDF).

D.2.1.1 Risk-Mitigation Options for Grout Case I

Grout case I is predicated on the assumption that a grouted waste form 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 D.1.4, recent studies have suggested that some grout formulations have potential for good performance characteristics—particularly with respect to Tc retention. But additional research would be needed to confirm the improved retention of Tc relative to waste form performance in IDF and to demonstrate the improved performance by incorporation of these results into a formal performance assessment. **[NEED TO INSERT STATEMENT HERE BASED ON THE MINI-PA RESULTS WHEN AVAILABLE]** 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 D-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](#)).

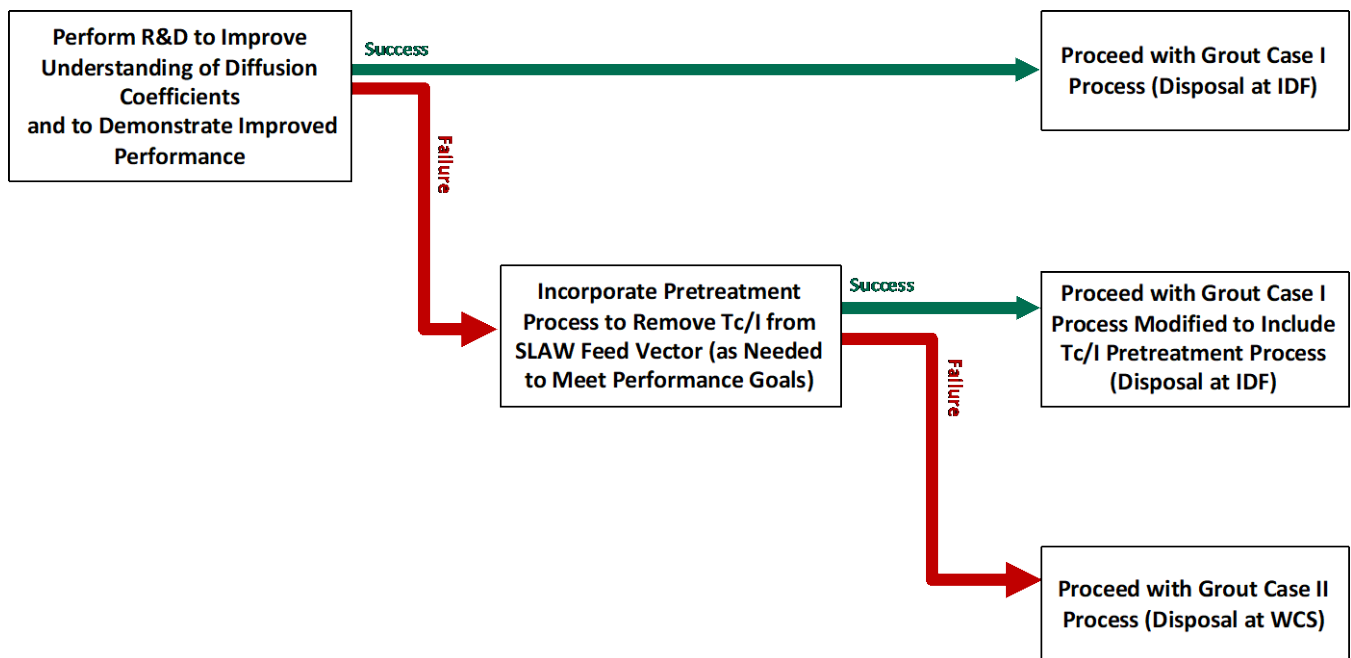


Figure D-6. Risk-mitigation logic for grout case I relative to primary risk associated with demonstrating acceptable performance for grout relative to retention of Tc/I.

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

D.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 waste form should an issue arise with the curing of a particular batch.

D.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 D-7, which assumes disposal of the grouted monoliths at the Waste Control Specialists (WCS) facility in Texas. The WCS facility can store and dispose 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 waste form 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. [NEED REFERENCE]

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.

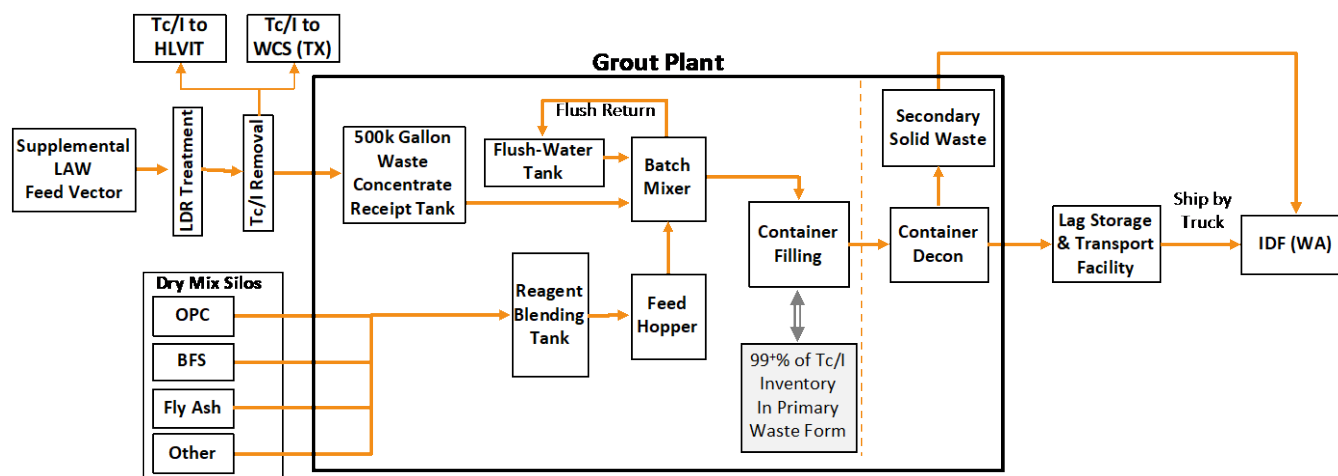


Figure D-7. Process flow diagram for the case II scenario considered for the grout process, where the final Cast-Stone monoliths are disposed of at the WCS facility in Texas.

D.2.3 Other Grout Options Considered

Several other cases were considered in the assessment before settling on grout cases I and II. Table D-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 waste form 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 D-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 HLVT)	Tc/I (sent to WCS)	Sr (sent to HLVT)	
	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

D.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 may be present in the SLAW feed. This assumption impacted the decision that pretreatment to destroy organics is likely needed for any disposal site considered for grouted SLAW.
- Recent data showing lower values in release of Tc/I reflect more accurate measures of expected effective 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.

D.4 RISKS

D.4.1 Waste Acceptability

The acceptability of the waste form was recognized as a potential risk with grout as an option for SLAW at IDF. Grout waste forms have not been permitted for disposal at the IDF, and the State of Washington has explicitly questioned the use of a grout waste form. 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 waste form
- The removal (by pretreatment) of radionuclides of potential concern (Tc and I).

For all primary SLAW waste form 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, this represents a risk for all primary SLAW waste forms, 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 waste forms 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 D.1.4, several recent studies have shown the potential for a grouted waste form to retain technetium 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 potential impact of the process to address LDR organics on the performance of the grouted waste form.
- 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 D.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.

D.4.2 LDR Constituents

Any acceptable pathway for grout as a waste form (either at IDF or WCS) will require addressing the potential presence of organics associated with LDR under RCRA. Grouted waste forms 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 D.2.1 and D.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 waste form, which may be a particular concern for technetium. This risk is addressed above in the recommendations for additional testing in Section D.4.1. This risk applies to IDF only.

Any acceptable pathway for grout as a waste form (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 waste forms 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.

D.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
- *Inability to Develop an Effective Pretreatment Process for LDR Constituents.* This applies in particular to the potential need for a pretreatment step for LDR organics; the TRL for this process was estimated to be medium (4–6) based on details provided in Appendix B.3.4, which include the need to integrate a process to destroy organics without impacting the retention characteristics of grout for redox sensitive constituents.

- *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.

D.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:

- *Less off-gas, hence less secondary waste.*
- *Start/stop flexibility*
- *Elimination of potential worker safety concerns associated with high temperature processes*

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.

Other benefits of grouting include:

- *Least-complex process of three options considered*
- *Lowest secondary waste volume due to minimal off-gas treatment and no liquid secondary waste stream*

Cost estimates for the grout process are detailed in Appendix J. Grout has the lowest estimated costs among the options evaluated, ranging from ~\$2–10 B for grout cases I and II.

D.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 L for details).

D.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 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 waste forms 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 m³ (G.5.2), whereas the projected volume of grouted supplemental LAW would be ~370,000 m³. Grouted supplemental LAW is not currently permitted at the IDF facility.

D.8 OBSTACLES

Obstacles for grout as an option to address SLAW include:

- *Grout is not permitted at IDF.* This obstacle applies only to grout case I (disposal at IDF).
- *Acceptable grout performance needs to be demonstrated.* This obstacle also applies only to grout case I. 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.

D.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 E. EXPANDED DISCUSSION – PRETREATMENT

E.1 ASSUMPTIONS

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. Additional pretreatment could allow waste forms that have unacceptable performance to be considered in as alternatives to glass. These pretreatment processes may remove I, Tc, or other components as needed to allow the alternative waste form 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.

E.2 REQUIREMENTS

E.2.1 LDR Organics / Metals

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 approximate 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 E.1:

- 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 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 E.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. However, in many cases the 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 reporting limit concentration. In this case a number of additional compounds could have exceeded the LDR standard.

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 99.9%..

Table E.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 waste form for selected waste forms. 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 waste form would meet LDR requirements.

E.2.2 Technetium

The removal of Technetium is part of a potential mitigation strategy to be employed as needed to ensure that the SLAW grout meets the 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 Immobilized Low Activity Waste (ILAW) grout.
- LSW performance extrapolation is linear to much higher Tc inventories.
- Fraction of Tc inventory for 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 ~92.2% would be required for a grout waste form. To limit the groundwater concentration to 100 pCi/l an overall Tc removal of 99.1% would be required.

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.

E.2.3 Iodine

The basis for the iodine (I) removal is the 2017 IDF PA. The underlying assumptions are that:

- LSW grout is conservative relative to performance of ILAW grout
- LSW performance extrapolation is linear to the iodine inventories
- Fraction of I inventory in LAW to be sent to SLAW is 50-60% of that to be sent to the LAW facility.

Based on these assumptions and a maximum groundwater limit of 1 pCi/l to meet regulatory requirement an overall iodine removal of ~48-57% would be required for a grout waste form. To limit the groundwater concentration to 0.05 pCi/l an overall I removal of 97 - 98% would be required.

It should be noted that the performance of ILAW grout formulation may be significantly better than the LSW grout; with regards to iodine retention, therefore, the required pretreatment evaluated is assumed to be conservative.

E.2.4 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 E.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 E.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 E.2. Impact of Sr removal on Waste Classification for Grout

Grout (1770 kg/m ³ , 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 E.3. Impact of Sr removal on Waste Classification for vitrified or Steam Reformed Waste

Glass or Steam Reformed (2600 kg/m ³ , 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 Supplemental LAW 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 resorcinol-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.

E.3 SELECTED PRETREATMENT TECHNOLOGIES

E.3.1 LDR Organics/Metals

E.3.1.1 LDR Organics

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 (H₂O₂) in the presence of ferrous iron (Fe²⁺) produces Fenton's Reagent which yields free hydroxyl radicals (•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 E.1 is presented in Table E.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, NO_x, etc but results in the formation of intermediary compounds.

As noted previously not all these compounds are present in all tanks. In addition, the possible levels shown in Tables E.1 and E.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 times the concentration-based standard there was no chemical oxidation effectiveness data found. This level of exceedance would require ~82% destruction.

Table E.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*	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	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	No reference found	No reference found
Morpholine, N-nitroso-	59-89-2	137	No reference found	No reference found
2-Propanone	67-64-1	126	No reference found	No reference found
Methanamine, N-methyl-N-nitroso-	62-75-9	113	No reference found	No reference found
2-Butanone	78-93-3	104	Not reactive	Not reactive
1-Butanol	71-36-3	95.9	No reference found	No reference found
Pyridine	110-86-1	75.5	No reference found	No reference found
Methanol	67-56-1	49.1	Oxidizes to formic acid	Oxidation with V ₂ O 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 reference found. Likely to react with nitrile bond	--
Acetonitrile	75-05-8	7.6	No reference found	No reference found

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	No reference found	No reference found
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	--

E.3.1,2 LDR Metals

Bhattacharyya, et al. (2006) found that sulfide precipitation with Na₂S 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/l 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).

E.3.2 Technetium

E.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 ¹²⁹I, ⁷⁵Se, and ⁹⁹Tc, from caustic solutions containing high concentrations of nitrate, nitrite, and carbonate. In this approach the anionic species such as I⁻ and TcO₄⁻ 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 DtBuCH₁₈C₆ 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 HNO₃. 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.

E.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 (TcO₄⁻). 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 E.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 E.5. Batch distribution ratios (K_d) for sorption of Tc from a Hanford Tank Waste Simulant containing organic complexants (Wilmarth, et al., 2011)

Ion exchanger	Description	K_d , 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
<i>n</i> -butyl-Reillex HP	<i>n</i> -butyl derivative of poly-4-vinylpyridine/divinylbenzene (Reillex™ HP)	1,405
iso-butyl-Reillex HP	iso-butyl derivative of Reillex™ HP	810
<i>n</i> -hexyl-Reillex HP	<i>n</i> -hexyl derivative of Reillex™ HP	1,405
<i>n</i> -octyl-HP	<i>n</i> -octyl derivative of Reillex™ HP	780
TEVA-Spec	Methyltricaprylammonium chloride (Aliquat™ 336) sorbed onto an acrylic ester nonionic polymer	1,280
Aliquat 336 beads	Aliquat™ 336 sorbed onto porous carbon beads (Ambersorb™ 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).

E.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 absorbants, 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%.

E.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.

E.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 NaNO₃, has been developed by Kocherginsky, et al. (2002). Using liquid extraction-re-extraction, 98% of Sr was removed at a rate of $4.5 \times 10^{-9} \text{ mol} \cdot \text{s}^{-1} \cdot \text{L}^{-1}$.

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.

E.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:

“sodium titanium silicate, $\text{Na}_2\text{Ti}_2\text{O}_3\text{SiO}_4 \cdot 2\text{H}_2\text{O}$ (NaTS), was the best material in NCAW with a K_d of $2.7 \times 10^5 \text{ mL/g}$ 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_d s 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 titanate 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 $\text{Sr}(\text{NO}_3)_2$ 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 titanate, 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_d s) of 220 mL/g at a volume-to-mass ratio of 200. However, for the 107-AN simulant, the titanate 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 titanate (Sylvester and Clearfield, 1999). Based on these findings 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

E.4 APPROACH TO PRETREATMENT

The conceptual flow sheet for the two grout cases is shown in Figure E.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 LDR 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 verify 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 waste form not meeting the desired Performance Assessment goals. In these cases, Tc and/or iodine removal as a pretreatment step would be considered. Additional LDR metal pretreatment is also considered as a potential mitigation process if the resulting waste form 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 implemented as either mitigation or as an opportunity to alter the waste classification is shown in Figure E.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 LDR 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 waste form), 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™. 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.

Summary of areas for additional R&D:

- Improved analytical methods to quantify levels of LRD organics in the feed vector.
- Maturation of each of the primary technologies to TRL 8.
- Significant work remains to demonstrate the removal of iodine from caustic waste streams.
- Development of an iodine waste form compatible with the removal method.
- Demonstration of large scale ozonation system.
- R&D is needed to demonstrate the oxidation of the full range of LDR organics either with ozone alone or in combination with permanganate.
- o *Determine mixing parameters, residence time, oxidation rates, etc.*
- R&D is also needed to determine if the chemical oxidation results in the formation of other LDR organics.
- Demonstration / confirmation that grout formulations will pass TCLP as is, or with additional pretreatment, for LDR metals
- Additional R&D is needed to understand the extent of Sr removal in the WPT Pretreatment Cs removal using CST.

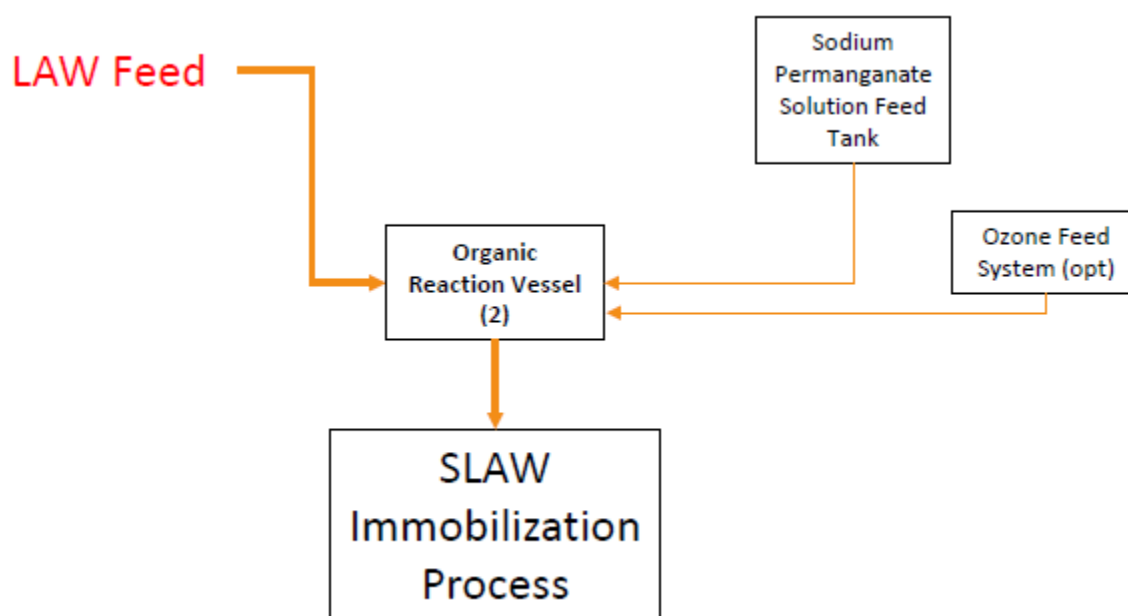


Figure E.1. Supplemental LAW Pretreatment Concept with LDR organic treatment only

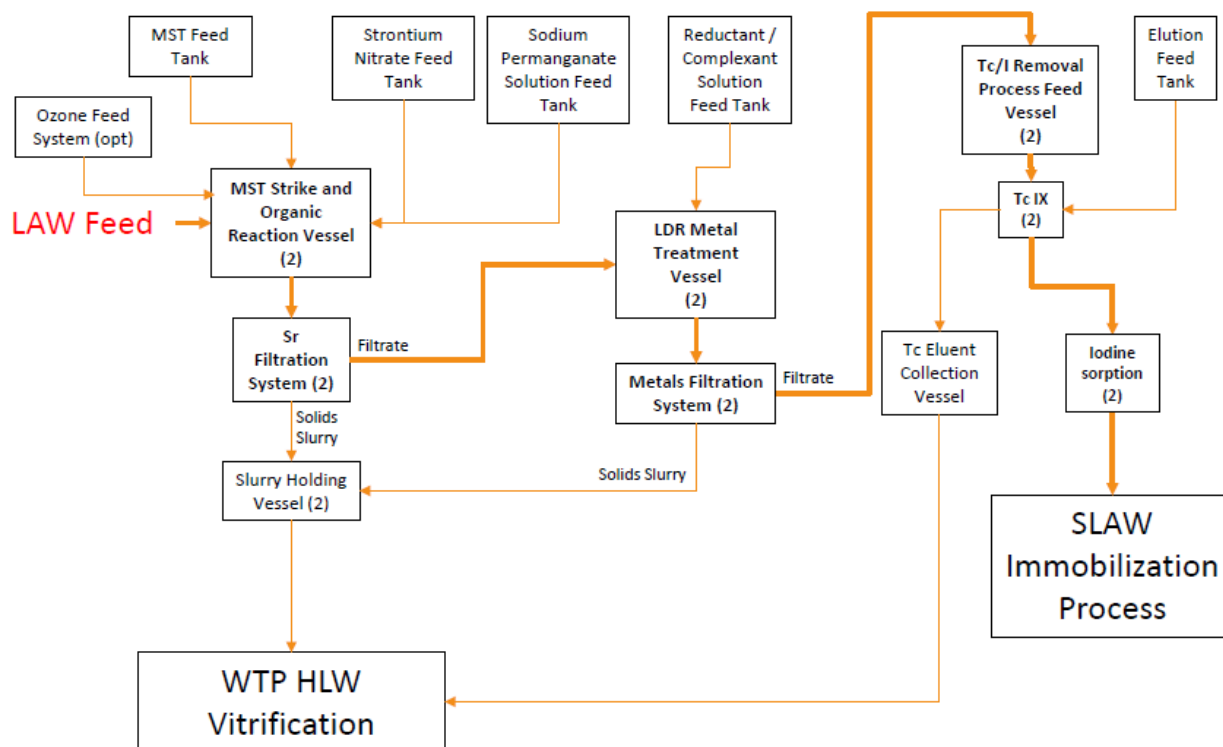


Figure E.2. Supplemental LAW Pretreatment Concept with Tc, I, LDR metal, and Sr removal

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APPENDIX F. EXPANDED DISCUSSION – OTHER APPROACHES

TBD

APPENDIX G. EXPANDED DISCUSSION – DISPOSAL SITE CONSIDERATIONS

G.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 on-site at Hanford and is being developed by the DOE. The second disposal facility, the Waste Control Specialists (WCS) facility, is off-site and is a commercially-operated disposal facility licensed by the State of Texas (a NRC Agreement State⁸⁶).

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 on-site facility is more limited in its ability to fully accommodate wastes with higher concentrations of I-129 and Tc-99, but no off-site 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 G.5.4.3, the immobilized SLAW will classify as Class B and C MLLW for off-site disposal (no Class A). The Clive facility can only accept Class A LLW and MLLW for disposal, and therefore the Clive facility will not be discussed further. Should the Sr-90 be removed from the SLAW, the immobilized waste forms (WFs) would then be classified as Class A MLLW (Section G.5.6), and Clive would be a viable off-site alternative to WCS, with a shorter shipping distance and competitive disposal fees.

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)⁸⁷ for the IDF, this Appendix will present the results of a disposal performance evaluation for the primary and secondary WFs. The WCS facility does have a radiological WAC, which will be presented and used to classify the primary and secondary wastes for disposal. Disposal cost considerations for the WCS will also be addressed in section G.5.5.

G.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.

⁸⁶ 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.

⁸⁷ As used here, WAC are the criteria the wastes must meet to be acceptable for disposal.

G.3 WASTE FORM CHARACTERISTICS IMPORTANT FOR DISPOSAL

G.3.1 Characteristics of Wastes to be Immobilized

The characteristics of the SLAW that will be immobilized for disposal are described by the SLAW Supplemental Treatment Feed Vector (or simply the Feed Vector), which is discussed in detail in Section 2.2. 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-period⁸⁸.

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, Table G-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 G-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			

⁸⁸ 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 G-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 G-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 G-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 importation 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 G-3 provides summary statistics from the Feed Vector for the *volume of SLAW* that will be immobilized and disposed; a total of 54,000,000 gallons (204,400 m3).

Table G-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 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).

G.3.2 Characteristics of the Vitrified Waste Form and Secondary Wastes

Vitrification and the vitrified WF are detailed in Section 4.2. The specific characteristics important for using the Feed Vector to characterize the vitrified WF for disposal are presented in Tables G-4 and G-5.

Table G-4 Characteristics of the Vitrified Waste Form – Canister

Volume change caused by vitrification	0.4 (decreases volume & increases specific activities)
Density of final WF	
Solid Secondary Wastes	detailed in G.5.4.4 Classifying Secondary WFs
Pretreatment waste	No cases
Total volume Vit (204,400 m ³ x 0.4)	81,760 m ³
Average volume / month (w/337 months)	243 m ³ / month

Table G-5 Characteristics of the Vitrified Waste Form - Bulk

Volume change caused by vitrification	
Density of final WF	
Solid Secondary Waste	Yes, always
Pretreatment waste	No cases
Total volume (204,400 m ³ x xx)	m ³
Average volume / month (w/337 months)	m ³ / month

G.3.3 Characteristics of Steam Reformed Case II Mineral Waste Form and Secondary Wastes

Steam reforming (Case II) and the Steam Reforming (Case II) 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 G-5

Table G-5 Characteristics of Steam Reforming Case II WF – Granular Mineral

Volume change caused by steam reforming	1.2 (increases volume & decreases specific activities)
Density of final WF	800 kg/m ³ (50 lb/ft ³)
Solid Secondary wastes	detailed in G.5.4.4 Classifying Secondary WFs
Pretreatment wastes	No cases
Total volume (204,400 m ³ x 1.2)	245,300 m ³
Average volume (total/337 months)	728 m ³ / month

G.3.4 Characteristics of Grout Case II Waste Form and Secondary Wastes

Grouting and the grouted WF (Grout Case II) 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 G-6.

Table G-6 Characteristics of Grouted Waste Form (Grout Case II)

Volume change caused by grouting	1.8 (increases volume & decreases specific activities)
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Density of final WF	1770 kg/m ³ (110 lb/ft ³) (0.0624 lb./ft per kg/m ³)
Solid secondary wastes	detailed in G.5.4.4 Classifying Secondary WFs
Pretreatment wastes	Yes, for 2e2 would create a PW for disposal at WCS, this is described in G.5.4.4
Total volume (204,400 m ³ x 1.8)	367,900 m ³
Average volume (total/337 months)	1092 m ³ / month

The characteristics of the immobilized WFs and information in the Feed Vector will be used together to assess the ability of each WF form to meet the waste acceptance criteria at the two disposal facilities.

G.4 INTEGRATED DISPOSAL FACILITY

G.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.

G.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.

G.4.1.2 Disposal Facility Design

The IDF currently consist of two disposal cells, with a capacity of approximately 300,000 m³, although the facility can be expanded as needed to a total capacity of six cells with a capacity of approximately 900,000 m³. The first two cells of the IDF were constructed in 2006 as shown in Figure G-1. The IDF consists of 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 G-2, and consist of 1) a modified 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 waste forms for structural support and to limit water from contacting the waste during disposal operations, 3) engineered backfill between and above waste containers to provide structural support

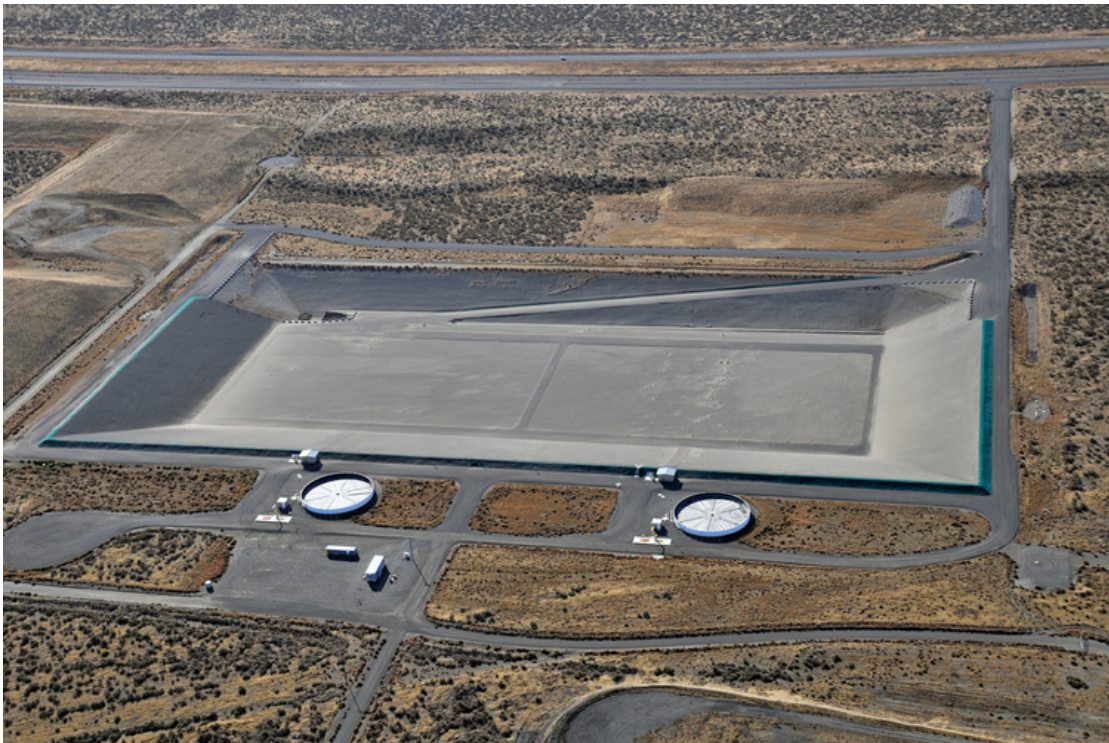


Figure G-1. Aerial View of the Two IDF Cells in the Hanford Site 200-East Area Southwest of WTP (a high point down the center of the liner system separates the two cells).

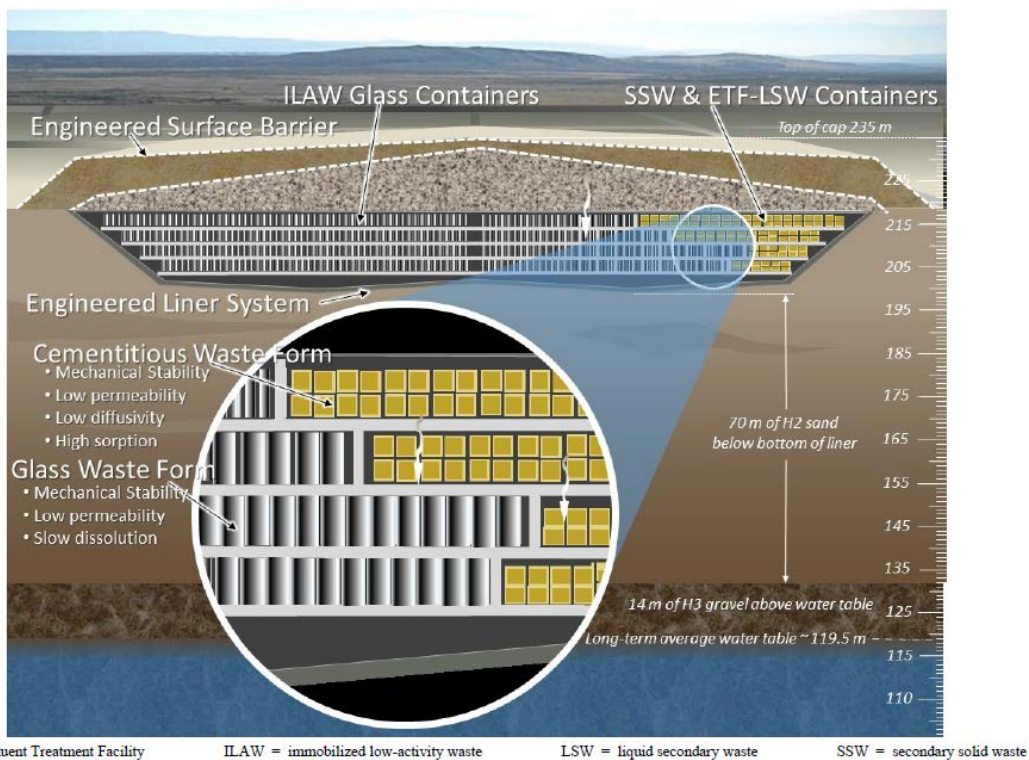


Figure G-2. Schematic Depiction of Engineered Safety Features of the IDF

during operations, and 4) 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. Cell 1 is for radioactive MLLW that contains dangerous or hazardous waste and is regulated under RCRA⁸⁹; Cell 2 is for radioactive only low-level 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.

G.4.2 Key Regulatory Requirements

For purposes of this analysis, only disposal in the RCRA permitted portion of the IDF is considered. The current WAC are documented within the RCRA dangerous waste permit⁸⁹. However, a final approved WAC has not yet been established. The current permit currently limits disposal at IDF to ILAW vitrified (glass) waste forms from WTP and 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. In addition, the PA contains results that can be used to address operating conditions or requirements specified in the RCRA permit for the disposal facility.⁴ A draft 2017 performance assessment for IDF was recently completed and is awaiting public release. Previously, DOE issued an initial PA for this facility in 1998⁹⁰ which was conditionally approved by DOE in 1999, and an update in 2001.⁹¹ A subsequent 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.

G.4.2.1 RCRA Permit and WAC

Washington State Department of Ecology (Ecology) recently issued Revision 9 of the Hanford site-wide dangerous waste permit, including Operating Unit Group 11 for the IDF. (Ref. 4 on prior page). 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 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 and SLAW processing, secondary wastes are 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 IDF⁹². This includes specific waste form 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

⁸⁹ Hanford Dangerous Waste Permit, Rev. 9. WA7 89000 8967, Part III Operating Unit Group 11, Integrated Disposal Facility Section III.11.C.5, Waste Acceptance Criteria and Waste Verification Requirements (<https://fortress.wa.gov/ecy/nwp/permitting/hdwp/Rev/9/OU/IDF.html>)

⁹⁰ 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.

⁹¹ Mann et al, 2001. Hanford Immobilized Low-Activity Tank Waste Performance Assessment: 2001 Version. DOE/ORP-2000-24, Rev. 0. U.S. Department of Energy, Richland, Washington.

⁹² IDF Permit (WA7 89000 8967), Section III.11.C: Waste Analysis/Waste Acceptance.

that models the future impacts of the planned IDF waste forms to underlying vadose zone and ground water, and compares results to various performance standards including drinking water standards. If modeling efforts project results within 75% of a performance standard, then the permit requires DOE and Ecology to meet to discuss mitigation measures or modified WAC for specific waste forms. 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.”

Other waste acceptance criteria for the IDF include:

- Wastes must be RCRA LDR compliant;
- Prohibit Transuranic and Greater than Class C (GTCC) wastes;
- Need to treat wastes that have the Waste codes D001 (ignitable), D002 (corrosive), D003 (reactive) 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 void space requirements for containers (i.e., must be >90% full);
- Waste packages cannot exceed 200 millirem/hr at 30 cm;

Presently, there are no on-site 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 off-site 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.

G.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} that focused principally on disposal of ILAW glass⁹³, two risk assessments that focused on expansion of the waste forms to be considered for disposal in the IDF including secondary wastes and supplemental LAW waste forms,^{94,95} and the Tank Closure and Waste Management EIS⁹⁶ 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 direction⁹⁷. 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.

G.4.3.1 2017 IDF Performance Assessment

⁹³ 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 supplemental LAW forms.

⁹⁴ Mann et al., 2003. Integrated Disposal Facility Risk Assessment. RPP-15834, Rev. 0, CH2MHILL Hanford Group, Inc. Richland, Washington.

⁹⁵ 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.

⁹⁶ DOE. 2012. Tank Closure and Waste Management Environmental Impact Statement. DOE/EIS-0391. U.S. Department of Energy, Richland, Washington.

⁹⁷ 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.

The IDF PA addresses DOE requirements that the analysis provides 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 G.X.1 identifies key analysis requirements, expectations, and assumptions used in the 2017 IDF PA.

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.⁹⁸ 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,

⁹⁸ 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.

Table G.X.1. 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	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
Period of Institutional Control	100 years (E)	Assumed leachate collection and leak detection are operable. No public 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		

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.

The development of a durable waste package (including the waste form 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 waste forms that provide physical,

chemical and thermal barriers inhibiting radionuclide release. Waste forms in the shallow land burial site must also be able to sustain the weight of soil overburden and potential intrusion. Resistance to leaching, fracturing and other modes of degradation are key characteristics that minimize waste form 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. The vast majority of the key contaminants of concern present in tank waste—Tc-99 and I-129—are to be treated and disposed via ILAW, SLAW, and the secondary wastes generated from LAW processing. 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 waste form. For example, Figures 5-10 of the EIS is reproduced below, 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 on the plateau peak around year 3900 at groundwater concentrations approximately 2 to 2.7× MCLs identified as the “benchmark concentration” in the figures. Figure 5-21 of the 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.

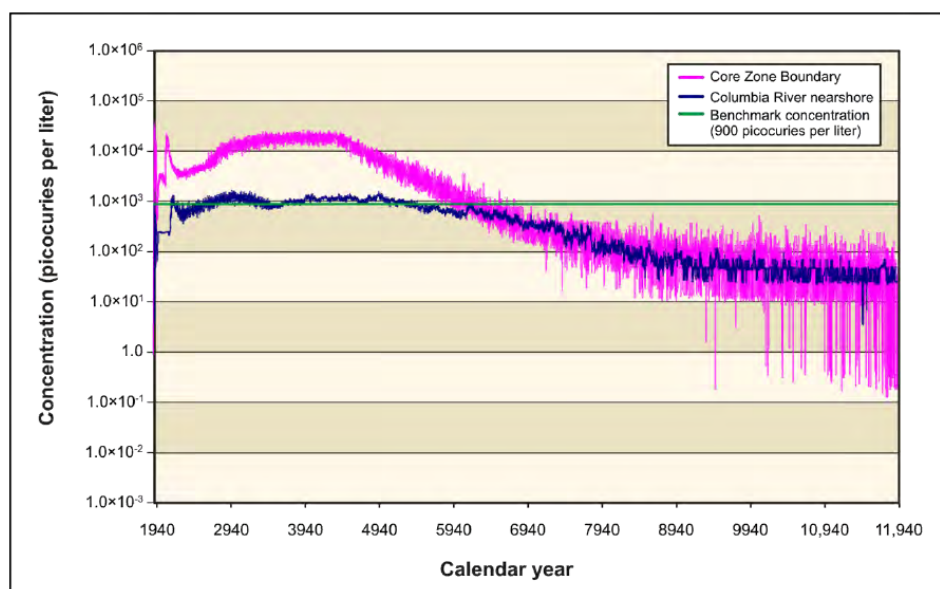


Figure 5-10. Tank Closure Alternative 1 Technetium-99 Concentration Versus Time

Figure G-3. Impacts to Groundwater of Untreated Tank Waste from the TC&WM EIS, No Action Alternative.

The 2017 IDF PA considered two potential waste form releases from LAW and SLAW processing: 1) glass; and 2) non-glass (cementitious) secondary waste forms. Glass, as the end-product of waste vitrification, is considered a more stable waste form relative to cement-based waste forms. 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 chemical bonds break and contaminants are released. For cementitious waste forms, 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 waste forms. Release models evaluated radionuclide release, which were then considered as source terms for a vadose zone fate and transport model.

The primary waste forms from LAW processing that were analyzed in the 2017 IDF PA included:

- The primary ILAW Glass waste form (ILAW Glass) generated from vitrification of the LAW feed stream, including the SLAW 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 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 the LAW or SLAW 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 performance objective.
- For the air and groundwater 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 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 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 did not consider alternative waste forms beyond ILAW glass for SLAW, and the corresponding secondary wastes generated from SLAW glass production. Therefore, to address IDF waste form performance of alternative SLAW waste forms and any secondary wastes generated from SLAW processing, additional modeling and performance evaluation is necessary.

G.4.3.2. SLAW Performance Evaluation Strategy and Approach

The strategy identified to address evaluation of the alternative SLAW waste forms and their secondary wastes was based on review of the 2017 IDF PA technical approach, results, and identification of advances in waste form development and modeling that were not considered in prior SLAW analysis, such as the PA, TC&WM EIS, or 2003 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 waste form. Explicit coupling of 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 waste form 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 waste forms where geochemistry is needed to describe the waste release. The strategy is to use a reactive transport code to simulate the waste form degradation, especially for the glass and steam reforming materials, where their degradation is dependent on matrix dissolution.
2. **Waste form stacking scenarios within the facility.** The 2017 PA identified how stacking lifts of different waste form containers could impact potential changes in vertical saturation distributions within the facility. Although impacts on waste form dissolution rates were examined for like waste forms 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 waste forms was also not simulated in the PA, but separate studies have indicated potential impacts of intermingled waste forms. The strategy is to simulate a full stack of lifts for each waste form. Potential interactions from different intermingled waste forms will not be addressed in this strategy, as it is assumed that operational vs. waste form release tradeoffs will be assessed in future performance assessments, and the IDF can accommodate separation of dissimilar waste forms if necessary.
3. **Waste form systems.** The 2017 PA explicitly analyzed ILAW glass and cementitious secondary waste forms, but did not consider advanced glasses, steam reforming product, ILAW grout and secondary wastes from these alternative non-glass supplemental LAW treatment waste forms. In addition, there has been advancement in understanding of both steam reforming product and ILAW grout waste form 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 waste forms. The strategy is to use the IDF PA results for those waste forms where the PA represented the best current technical basis (i.e., ILAW glass and secondary waste), and use updated waste form performance understanding for steam reforming product and ILAW grout waste forms. Best available inventory information will also be used in this study.

The primary objective of the NDAA waste form disposal performance evaluation is to assess and compare the performance of the various SLAW waste form options under consideration for disposal within the IDF, using the most current information available on contaminant inventory, waste form mechanism of release, and waste form performance. Waste form performance is one of the most significant factors that impacts the release flux and ultimate dose estimate. Computer models are used to simulate waste form degradation and the release and transport of radionuclides to the unconfined aquifer. In the NDAA assessment, eSTOMP is used (Fang et al. 2018) [the scalable version of STOMP (White et al. 2018)]. The eSTOMP simulator is capable of simulating contaminant release from the waste forms, transport and feedback mechanisms through the engineered system, and transport through the vadose zone to the groundwater (McGrail et al. 2003). The serial version of STOMP was used to simulate waste form releases in the 2017 PA. Both STOMP and eSTOMP are managed as NQA-1 quality software and have undergone quality assurance testing and verification for use in this type of analysis. Although there exist important feedback mechanisms that can affect waste form dissolution rates, it is anticipated that the impact of decoupling flow, reactions and transport is minimal once the interactions between the near-field environment and the waste form reach steady-state. Therefore, the focus of this study will be on modeling near-field release and transport of key radionuclides (i.e., ^{99}Tc and ^{129}I) from each waste form to obtain projected flux rates out of the IDF as a function of time, and use existing PA analysis and results

to equate the release from the total system of primary and secondary waste forms for each SLAW processing option, to groundwater impacts over time, to enable direct comparison of the alternative SLAW options with regard to the primary performance measures of interest.

A general approach for the evaluation of materials behavior in a disposal site was initially developed nearly twenty years ago. This approach outlines 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. For waste form degradation, the same computational framework used to conduct the 2017 IDF PA will be used for simulating near-field releases from glass, steam reforming product, and grout-encapsulated ILAW and secondary waste forms. The only difference between the two analyses is in the number of stacked waste forms. Only two lifts were simulated in the 2017 PA. The maximum height of the IDF facility is considered in this analysis, allowing for up to eight containers (depending on the height of the waste package) to be represented in the simulation.

Three separate systems of secondary low-activity waste (SLAW) are simulated, each with a different mix of waste forms based on inventory and feed vector estimates as shown in Table G.X.2. These waste forms are considered to be part of the same system because pretreatment and LAW processing not only create a targeted waste form (e.g., glass, ILAW grout or steam-reforming product), but also generate solid and liquid secondary wastes. As shown in the vitrification reference case above,

Table G.X.2. Primary LAW and SLAW Waste Form Systems for IDF Evaluation

Analysis Case	Primary LAW Waste Forms		Supplemental LAW Waste Forms	
	LAW	Secondary Wastes	SLAW	Secondary Wastes
1. Vitrification Reference Case (2017 IDF PA)	ILAW Glass	LSW - ETF SSW - HEPA filters SSW - GAC absorber	ILAW Glass	LSW - ETF SSW - HEPA filters SSW - GAC absorber
2. Grout Case 1			Cast Stone	SSW - HEPA filters SSW - GAC absorber
3. Steam Reforming Case 1			FBSR Mineral - Macroencapsulated	SSW - HEPA filters SSW - GAC absorber

the fabrication of the glass waste form also results in secondary liquid and solid wastes that will be converted to stable solid waste forms to be disposed of in the IDF.

For each LAW system evaluated, a contaminant-specific total effective flux to the environment is calculated by summing the waste form-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 PA.

A brief description of each of these four systems of waste forms is provided below, along with a description of their inclusion in this study.

ILAW Glasses. The baseline ILAW glasses were assessed in the 2017 PA, and further analysis is unnecessary. 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. The 2017 PA did not include advanced glasses because of the lack of characterization data needed to parameterize waste form behavior. When dissolution rates for advanced glasses are available, they should be included in a future performance evaluation. However, the advanced glasses will not be considered in this study. However, a benchmark simulation of the baseline glasses was executed to compare results with the 2017 PA.

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, charcoal, and a catalyst; aqueous LAW is converted to a granular, mineralized waste form while converting organic components to CO₂ and steam, and nitrate/nitrite components, if any, to N₂. Prior analysis in 2003 (McGrail et al.) and 2014 (EIS reference) presented widely varying performance predictions for steam reforming product. Since then, parameters describing its dissolution behavior have been updated, and this study can identify its potential behavior within the IDF, although variability in the mineral phase assemblages produced may have a significant impact on steam reforming product performance.

Grouted Secondary Waste. Processing of the SLAW feed vector will generate secondary wastes, including solid secondary waste (SSW) from the offgas treatment systems such as HEPA filters and carbon absorption 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 waste form to be disposed of in the IDF. Because LSW and SSW from ILAW vitrification was included in the 2017 PA, and the waste form performance parameters used are the most current available, further analysis of secondary waste grout is unnecessary. However, a benchmark simulation of the SSW and LSW was executed to compare results with the 2017 PA, and produce the needed flux information to apply to secondary waste from all SLAW processing alternative.

Grouted ILAW Waste. Development and testing of both grouted ILAW and secondary wastes from ILAW 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 ILAW waste form that is part of this study options. New data and formulations for cementitious waste forms from LAW waste streams are now available and include data on ⁹⁹Tc leach testing as a function of pH, the effective diffusivity for ⁹⁹Tc and ¹²⁷I, and desorption and solubility estimates for ⁹⁹Tc. The analysis of this study includes grouted ILAW performance.

G.4.3.3. Comparison of Performance Evaluation Basis Between TC&WM EIS, IDF PA, and NDAA Study

Waste form disposal performance evaluation of ILAW and SLAW waste forms 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 waste forms. 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. Waste form performance parameters, understanding, and assumptions about contaminant release and distribution
3. Assumptions regarding 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 formally 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 EIS, 2017 IDF PA, and the current integrated flowsheet system plan 8 feed vector, all three studies are based on different BBI bases that evolved over time.

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 G.X.3 summarizes the key inventory and distribution differences. A significant decrease (39%) in the BBI for I-129 occurred between 2002 (EIS basis inventory) and 2014 (IDF PA base case basis inventory), which is described in detail in the 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 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 waste form and secondary waste forms has substantially changed from that of the 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 Team chose to use the feed vector inventory, but apply split factors for the glass only case based on the more conservative IDF PA basis. This provides for better comparison to the current IDF analysis.

Table G.X.3. 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)	
Waste Forms	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						

Waste Form Performance

Similar to inventory, waste form 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 waste form 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 the time. The 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 waste forms, all studies have assumed a diffusion-controlled release from grouted waste forms. For ILAW grout, the TC&WM EIS used effective diffusion coefficients in a similar range (10^{-8} to 10^{-10} cm²/s) as that used in the original 2003 risk assessment based on limited laboratory studies. The IDF PA did not analyze an ILAW 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 EIS used the same effective diffusion coefficients for both ILAW grout and grouted secondary wastes. This study is using a range of effective diffusion coefficients based on the most recent ILAW 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 an ILAW steam reforming case. This study is relying on updated information describing both the minerals, distribution of CoCs into those minerals, and 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.

G.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. Given 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 waste form 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 waste form dissolution and/or contaminant release from each primary and secondary waste form, in order to estimate flux of the key radiological contaminants of concern impacting the IDF performance—⁹⁹Tc and ¹²⁹I. 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 PA near-field waste form degradation simulations. The benchmark simulations were executed for those waste forms 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 waste form stack scenarios executed in the 2017 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 that will supplement the 2017 PA analyses. This also provides confidence in the use of eSTOMP, the parallel version of the STOMP simulator, which allowed for significantly faster execution times. Release and dissolution rates used in these benchmark studies were based on laboratory measurements that were documented in data package reports 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 (McGrail and Bacon 2003). 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 waste form 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 waste form.
3. The benchmark simulation for LSW represents waste form 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 waste form.

Tables G.X.4. – G.X.6. 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 waste form 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 G.X.4. Rate Law Parameters for 2017 PA LAWA44 Glass at 15°C (Pierce et al. 2004)

$\bar{k}_0$		$K_g^{(a)}$	η	E_a	σ	r_{IEX}
Reported	Converted ^(b)	Glass Apparent		Glass		
Forward Rate	Forward Rate	Equilibrium		Dissolution		
Constant	Constant	Constant Based		Activation		
(g/[m ² d])	(mol/[m ² s])	on Activity	pH Power	Energy	Temkin	Na Ion-Exchange
		Product	Law	(kJ/mol)	Coefficient	Rate
		$a[\text{SiO}_2(\text{aq})]$	Coefficient			(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 G.X.5. Solid Secondary Waste Parameters

Secondary Waste Material	Contaminant Of Concern	Diffusion Coefficient	Distribution Coefficient	Reference
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		(cm ² /s)	(K _d) (mL/g)	
Silver Mordenite*	Iodine	5.40E-08	502	SRNL-STI-2016-00175
Grouted Carbon Absorber/Granular Activated Carbon (GAC)*	Iodine	5.40E-08	302	SRNL-STI-2016-00175
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	SRNL-STI-2016-00175
HEPA Filters*	Technetium	5.0E-06	0.0	IDF PA Table 5-27

*Executed as a benchmark simulation

Table G.X.6. Liquid Secondary Waste Parameters

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	0	IDF PA Table 5-37, Table 5-38
Iodine	Fly Ash	1.3E-09	4	0	IDF PA Table 5-37, Table 5-38
Technetium	Hydrated Lime	1.6E-09	0.8		IDF PA Table 5-37
Technetium	Fly Ash	1.3E-09	0.8		IDF PA Table 5-37
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

Two stacked waste forms and two different types of waste form boxes (B25 containers and 55 gallon drums) were simulated for LSW and SSW. Only a quarter of the waste form containers were represented in the simulation domain, assuming an axis of symmetry in the x- and y-coordinate directions, as shown in Figure G-4.

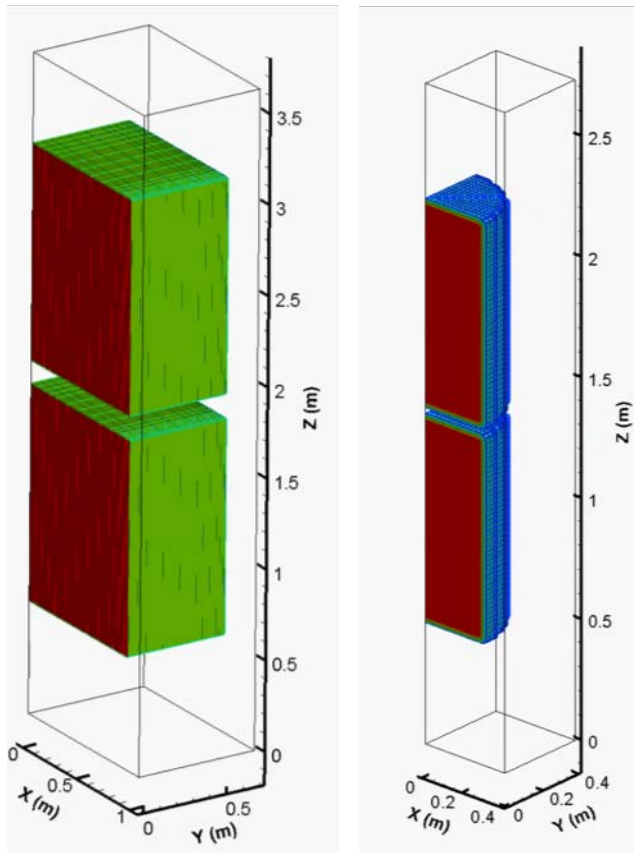


Figure G.4. Two container scenarios for the B-25 container (left) and the 55-gallon drum (right) for LSW and SSW simulations. Note only one quarter of the domain is simulated under an assumption of symmetry in the x- and y-coordinate directions.

The 2017 PA represented the glass domain in two-dimensions as shown in Figure G-5. Similar to the LSW and SSW simulation domains, two waste forms were represented but differ in size because the waste container dimensions differ.

Figure G-5 to be inserted

**Figure G-5..
2D
simulation
domain for
the LAW
glass
simulation
with two**

stacked waste forms.

A comparison of STOMP and eSTOMP simulation results are shown in Figure G-6. 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 share 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 G-4, eSTOMP was executed on 24 cores and executed up to 24 times faster than the serial STOMP simulations.

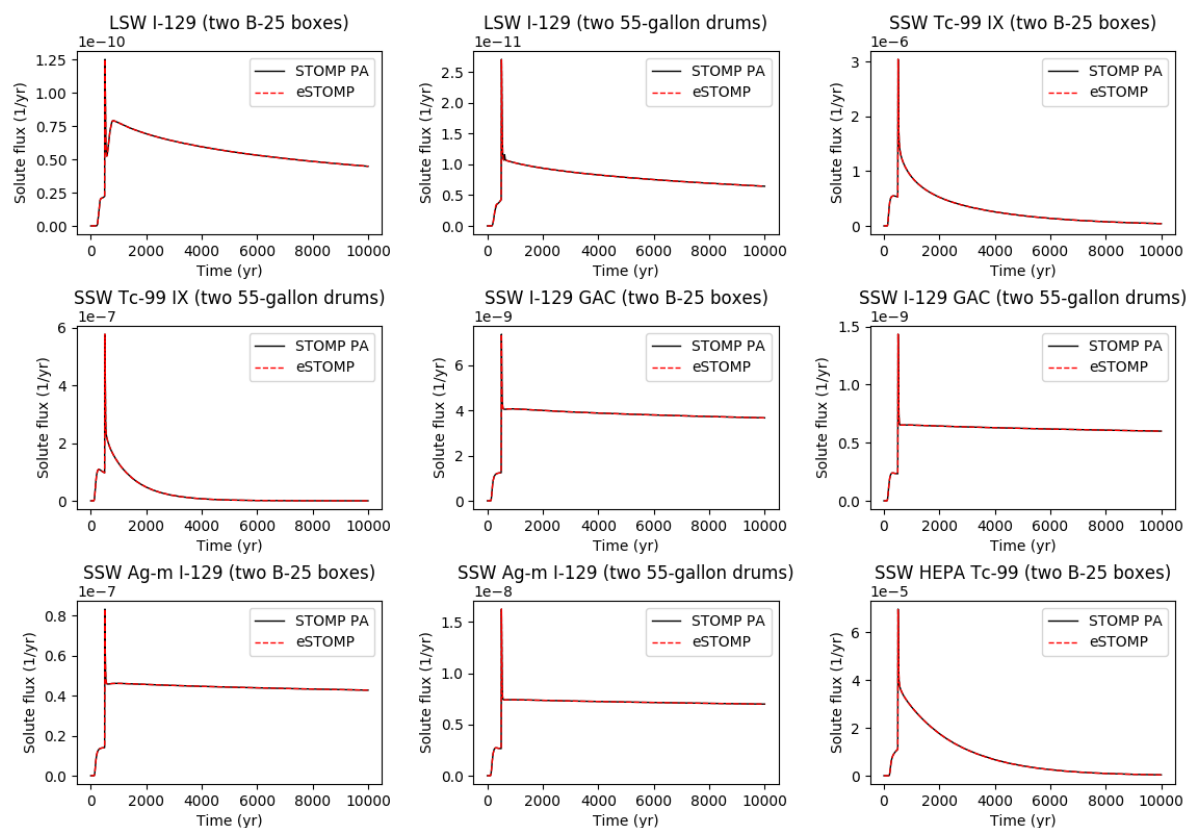


Figure G-6. Comparison of solute fluxes exiting the simulation domain for select LSW and SSW simulations. Benchmark results demonstrate that STOMP and eSTOMP yield the same results.

Figure G-7 shows a comparison eSTOMP and STOMP for ILAW 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.

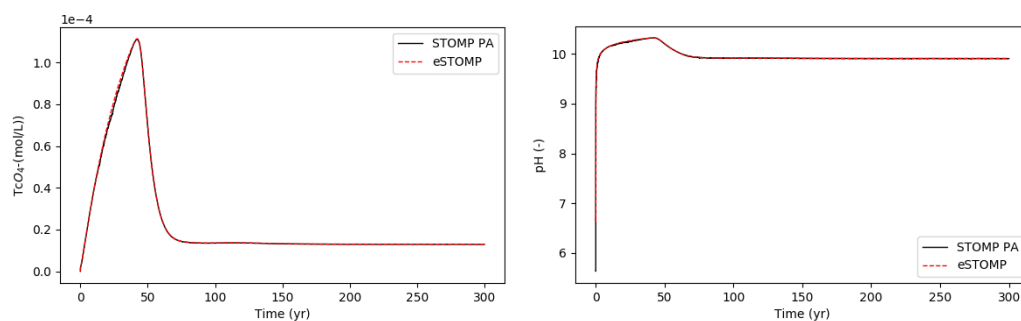


Figure G-7. Comparison of technetium-99 flux exiting the simulation domain (left) and corresponding pH (right). Benchmark results demonstrate that STOMP and eSTOMP yield the same results.

Supplemental Analyses and Simulations

The 2017 PA simulated a range of inventories that might occur, given that the Waste Treatment and Immobilization Plant (WTP) process flowsheet will evolve based on technical knowledge and regulatory decisions. Given that the *exact* inventory is unknown, the approach in this analysis is to assume an easily scalable inventory within each waste form 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 simulated in this analysis. The estimated inventories and splits are shown in Tables G.X.7. and G.X.8. for iodine and technetium, respectively. For example, if ILAW 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 and liquid secondary wastes (see Table 5). Subsequently, solute fluxes exiting the bottom of each domain will be scaled by the inventory distribution:

$$S_{iodine}^{Total} = [(S_{iodine}^{LAW})0.78736] + [(S_{iodine}^{SSW-HEPA})0.0062] + [(S_{iodine}^{SSW-GAC})0.2046] + [(S_{iodine}^{LSW})0.00184]$$

The total flux (S_{iodine}^{Total}) is then transported to the water table where groundwater concentrations can be used to calculate relative risks. These calculations are carried out for both Tc-99 and I-129 for the three waste form generation scenarios. In this way, relative risks are identified by waste form and scaled for the systems of interest.

Table G.X.7. Percent inventory splits for technetium-99.

Case #	ILAW Glass	ILAW Grout	Steam Reforming Product	SSW (HEPA)	LSW
1	99.9334			0.0661	0.0005
2		99.9934		0.0066	
3			99.9339	0.0661	

Table G.X.8. Percent inventory splits for iodine-129.

Case #	ILAW Glass	ILAW Grout	Steam Reforming Product	SSW (HEPA)	SSW (GAC)	LSW
1	78.736			0.620	20.46	0.184
2		99.7334		0.062	0.2046	
3			97.334	0.620	2.046	

In this relative impact analysis, the full stack of waste form packages is simulated for the maximum depth of the repository. For the B25 and 55-gallon containers, this means 8 waste packages are represented in the simulation domain. For the ILAW grout and steam reforming simulations, a maximum of 8 waste packages are also represented. Four waste packages are represented for the ILAW glass (see Figure G-8.).

Figure G-8 to be inserted

Figure G-8.

PLACEHOLDER FOR GRAPHIC DEMONSTRATING ALL OF THE SIMULATION DOMAINS

LAW Grout

The waste release mechanisms from grout waste forms 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 waste form 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 (see Table 6) and used in the transport models to predict the flux or rate of release of contaminants from the disposal system to the vadose zone.

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 m³), 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. Upper bound (higher diffusion coefficient) of recommended range of grouted ILAW performance based on laboratory testing
2. Lower bound (lower diffusion coefficient) of recommended range of grouted ILAW performance based on laboratory testing.
3. Lower bound sensitivity case based on laboratory testing of grouted ILAW using a disposal-relevant vadose zone pore water (VZPW) versus deionized water as the leachant, and with a potassium metal sulfide (KMS) Tc getter.

Key parameters needed for executing the ILAW Grout simulations are provided in Table G.X.9. Note that the Grouted LAW waste form release is described with an effective diffusion coefficient.

Table G-X-9. Grouted LAW Waste Parameters for SLAW Simulations

Contaminant of Concern	Redox Environment	Lower Bound Diffusion Coefficient (cms ² /s)	Upper Bound Diffusion Coefficient (cms ² /s)	Rationale	Reference/ Basis
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Technetium	Oxidized	5.0E-12	3.0E-10	Lower and Upper bound values of recommended range for LAW Waste Cast Stone from DIW testing, Westsik et al. 2013	Table 3.1, PNNL-25194, May 2016
Iodine	Oxidized	2.0E-09	2.0E-08		
Technetium	Oxidized	5.4E-13		Lower bound sensitivity case using VZPW, w/KMS getter	PNNL-25577, Rev. 0

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 stabilized (grouted). The grouted GAC and HEPA filters are specific to LAW and SLAW processing.

SSW parameters are the same as what was used in the 2017 PA and are given in Table G.X.5. The following scenarios were simulated for SSW:

1. Waste form degradation is simulated for an oxidizing environment, using a diffusive-advective transport approach. An effective diffusion coefficient represents geochemical interactions that retard diffusion from encapsulated HEPA waste form.
2. Waste form degradation is simulated for an oxidizing environment, using a diffusive-advective transport approach. An effective diffusion coefficient represents geochemical interactions that retard diffusion from encapsulated GAC waste form.

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 waste form 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.

LSW parameters are the same as what was used in the 2017 PA and are given in Table G.X.6. The following scenario was simulated for LSW:

1. Waste form degradation is simulated for an oxidizing environment, using a diffusive-advective transport approach. An effective diffusion coefficient represents geochemical interactions that retard diffusion from the reduced hydrated lime waste form.

Steam Reforming Product

Steam reforming forms a granular product that is encapsulated in a binder material to form a monolithic form that limits contaminant transport and provide structural integrity within the disposal facility. Steam reforming waste form 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 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 $\text{Tc}_2\text{S}(\text{S}_3)_2$, 2) laboratory waste form testing showed sodalite cage 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.

Similar to glass simulations, a reactive transport simulation approach will be used to simulate contaminant fluxes out of the disposal facility, assuming a solidified monolith and the ^{99}Tc is in both the nosean (McGrail et al. 2003) and pertechnetate sodalite (Schliesser et al. 2017) phases. Similar to the ILAW glass, transition state theory is used to represent the reaction rate law of the steam reforming product.

Specifically, the goal is to identify bounding scenarios, recognizing that the actual dissolution rate of the waste forms after emplacement will depend on the specific geochemical and hydrological characteristics of the IDF. Tables G.X.10 and G.X.11 contain data needed for executing steam reforming simulations. Steam reformed LAW is modeled with a reactive chemical transport simulator using updated thermodynamic data published in recent years (e.g., Schliesser et al. 2017, Pierce et al. 2016). Although a fifth non-pertechnetate bearing mineral has also been identified as low-carnegieite, no thermodynamic are available to date. Since low-carnegieite is a synthetic polymorph of nepheline, nepheline is used to represent halide bearing minerals within the waste form.

Two bounding scenarios are simulated that represent both reducing and oxidizing conditions.

1. 79 percent of the Tc-99 and I-129 inventories are present in the mineral cage and sequestered within nosean and pertechnetate sodalite phases. Hence, the CoCs are not immediately available for diffusion out of the waste form because they must undergo dissolution (similar to the LAW glass). The remaining 21% is assumed to be oxidized and immediately available for transport. While the data supports the 21% of Tc being in a reduced state, data and resources are not available to predict the re-oxidation behavior of this reduced phase in the current study. Therefore, a conservative assumption is applied to this remainder.
2. 56% of the Tc-99 and I-129 inventories are present in the mineral cage and sequestered within nosean and pertechnetate sodalite phases. Hence, the CoCs are not immediately available for diffusion out of the waste form because they must undergo dissolution (similar to the LAW glass). The remaining 44% is assumed to be oxidized and immediately available for transport.
3. 100% of the contaminants of concerns will be assumed to be present in the mineral cage, and thereby not available for diffusion out of the waste form. This scenario assumes that the process conditions that enable high incorporation of the contaminants into the cage structure is understood, and/or re-oxidation of reduced species is effectively controlled within the monolith structure. This represents a lower bound sensitivity case.

Table G.X.10. Rate law parameters for minerals in steam reformed product.

Mineral Phase	$\bar{k}_0$	$K_g^{(a)}$	η	E_a
	Converted ^(b) Forward Rate Constant (mol/[m ² s])	Equilibrium Constant Based on Activity Product $a[\text{SiO}_2(\text{aq})]$	pH Power Law Coefficient	Activation Energy (kJ/mol)
Nosean	2.5E-01	-92.1	0	48.6

Mineral Phase	$\bar{k}_0$	$K_g^{(a)}$	η	E_a
	Converted ^(b) Forward Rate Constant (mol/[m ² s])	Equilibrium Constant Based on Activity Product $a[\text{SiO}_2(\text{aq})]$	pH Power Law Coefficient	Activation Energy (kJ/mol)
Nepheline	1.0E-09	-9.39	-0.251	16.6
Pertechnetate sodalite	TBD	-6.23	0	TBD
Cl-sodalite	TBD	-1.21	0	TBD

Table G.X.11. Aqueous species and stoichiometry for minerals in steam reformed product.

Mineral	Aqueous Species	Stoichiometric Coefficient
Nosean	AlO ₂ 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 ²⁻	6.06
	Na	8.04
	SiO ₂ (aq)	5.94
	Cl ⁻	1.92
Pertechnetate-sodalite	AlO ₂ ²⁻	6.0
	Na	8.0
	SiO ₂ (aq)	6.0
	TcO ₄ ⁻	TBD

Simulation Results

Preliminary simulation results are presented in this section for two of the three waste form systems. Simulations for the steam reformed product have not yet been completed and will be included with the next revision of this report. In addition, only the first 2000 years of simulation are reported for the ILAW glass since this was the time period simulated in the 2017 PA. The glass simulation will also be updated with the next revision of this report, with an extension to 10,000 years since other waste forms (SSW, LSW and ILAW grout) have been simulated for the 10,000 year time period. Finally, the simulations will fully address the bounding scenarios in terms of waste form performance parameters for each waste form to fully address the range of key uncertainty that exists.

Results are only presented for a single set of parameters and one container type, using the highest-flux scenario to demonstrate the risk approach. For example, the largest effective diffusion coefficient was used for the ILAW grout simulations. Since the 55-gallon drums are smaller than the B-25 containers, flux concentrations are higher in the drums because the unit inventory is distributed over a smaller volume. Bounding parameters and the impact of container sizes will be investigated for all waste forms in the next revision of this report.

Results to date only report on flux out of the IDF and do not yet address the groundwater impacts associated with Tc-99 and I-129 fluxes once they enter the water table. In the next report revision, an analytical model will

be used to translate the solute fluxes to the water table, where concentrations can be directly related to IDF performance objectives and measures associated with each waste form and waste form systems.

Flux Predictions

Plotted in Figure G-9 are the fractional solute flux rates (based on an initial 1 Ci inventory) for both Tc-99 and I-129 for the three waste form systems described in Tables G.X.7 and G.X.8. Results are shown for each waste form that releases Tc and I into the facility. Note that for both solutes, the peak fluxes occur after 500 years, driven by the initial moisture content in the IDF once the waste forms are in place. Like the 2017 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. At 500 years, the surface barrier protecting the IDF is anticipated to degrade, and the recharge rate is increased to 3.5 mm/yr for the remainder of the 10,000 year simulation.

For Case 1, Figures G-9a and G-9b show that if the inventories were equal among the ILAW glass, SSW and LSW waste forms, the highest Tc-99 flux is from SSW, but the highest I-129 flux is from LSW. For Case 2, which is comprised of ILAW Grout and SSW, the SSW contributes the highest fluxes of both Tc-99 and I-129 as shown in Figure G-9c and G-9d. Case 3 is also plotted in Figures G-9e and G-9f, but since steam reformed simulations have not yet been completed, only the SSW fluxes are shown. However, both plots show the same fractional release rates as Case 2 for SSW since the inventories are the same.

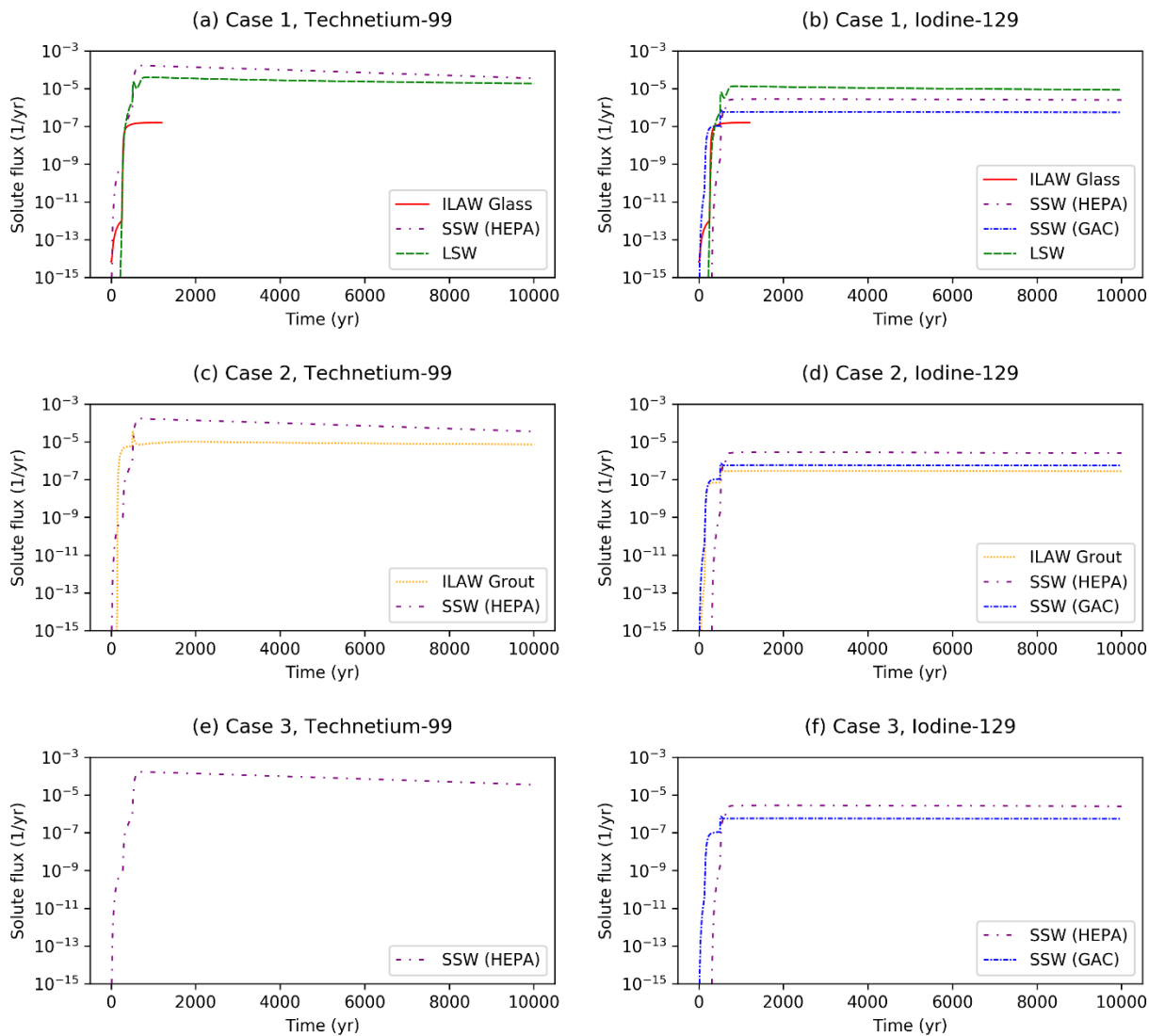


Figure G-9. Fractional solute fluxes from each waste form for technetium-99 (left) and iodine-129 (right) for the three waste form systems (Cases 1 – 3).

By contrast, Figure G-10 presents the fractional solute flux rates scaled by the inventory values reported in Tables G.X.7 and G.X.8. With an assumption of equal inventories, the solute fluxes for glass (Case 1) are lower than for LSW and SSW. With the scaled inventories shown in Figure G-10, the ILAW glass fractional fluxes are the largest contributors to the total flux exiting the facility for both Tc-99 (Figure G-10a) and I-129 (Figure G-10b). Although the total Tc-99 flux is approximately one order of magnitude higher than the ILAW grout (Figure G-10c), the I-129 flux from the ILAW grout (Figure G-10d) is nearly the same as the glass (Figure G-10b), implying a similar risk to groundwater for the two waste form systems.

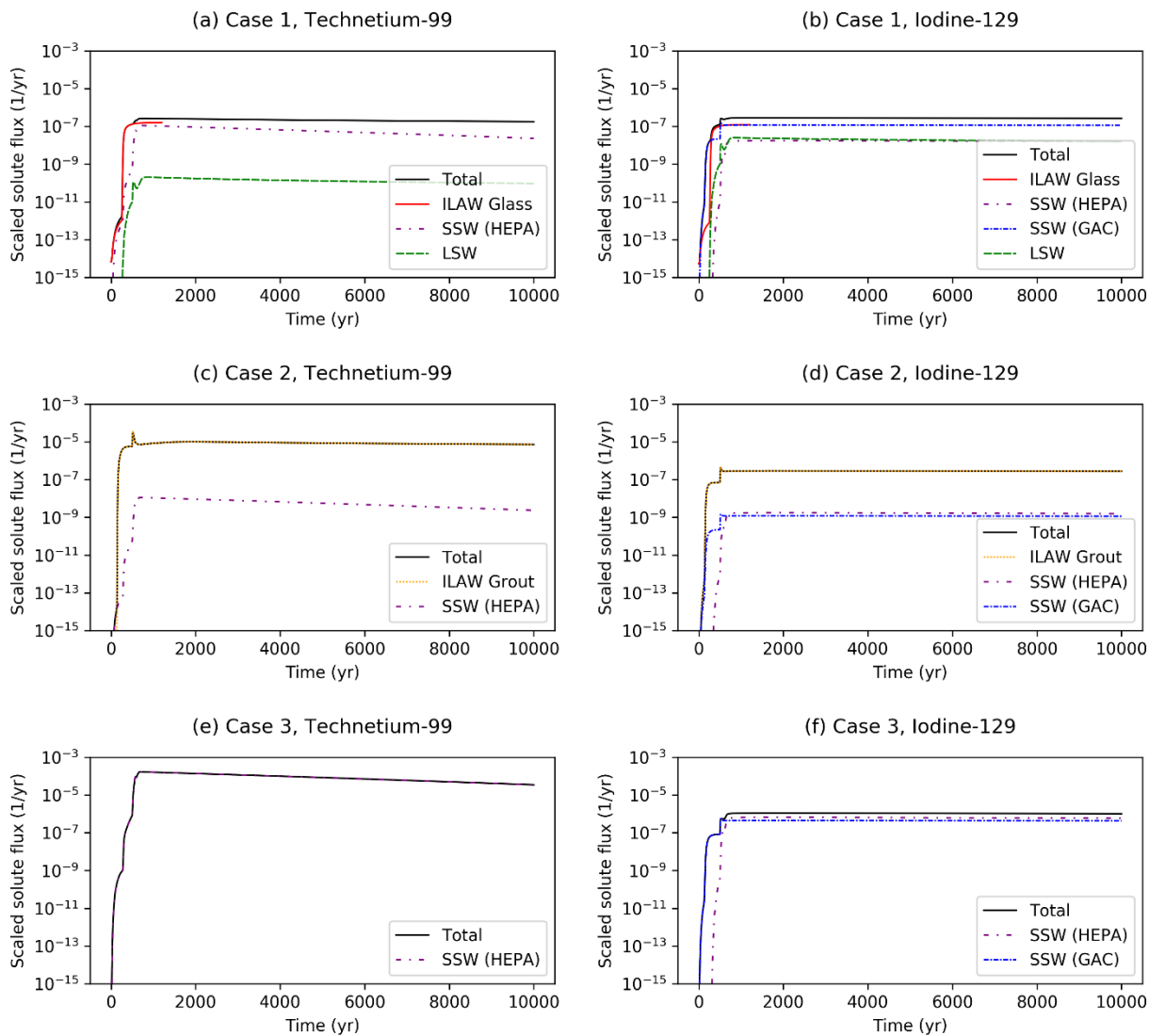


Figure G-10. Fractional solute fluxes from each waste form scaled based on total inventory for technetium-99 (left) and iodine-129 (right) for the three waste form systems (Cases 1 – 3). Black line in each plot represents the total scaled solute flux.

Cumulative Flux

Cumulative releases for Tc-99 and I-129 are shown in Figure G-11 and account for the solute released from each waste form within the system for Cases 1 – 3. Although the steam reformed system is incomplete, it shows that the cumulative inventory released from SSW with HEPA filters is near one curie. The impact on the total Tc-99 release for SSW with HEPA filters is also observed for Case 2, which has also nearly reached a one curie release by the end of the simulation. The cumulative radioactivity exiting the facility is nearly the same for all I-129 cases. This implies that the largest risk to groundwater is the Tc-99 flux resulting from ILAW grout, with a relatively similar risk from I-129 for the waste form systems.

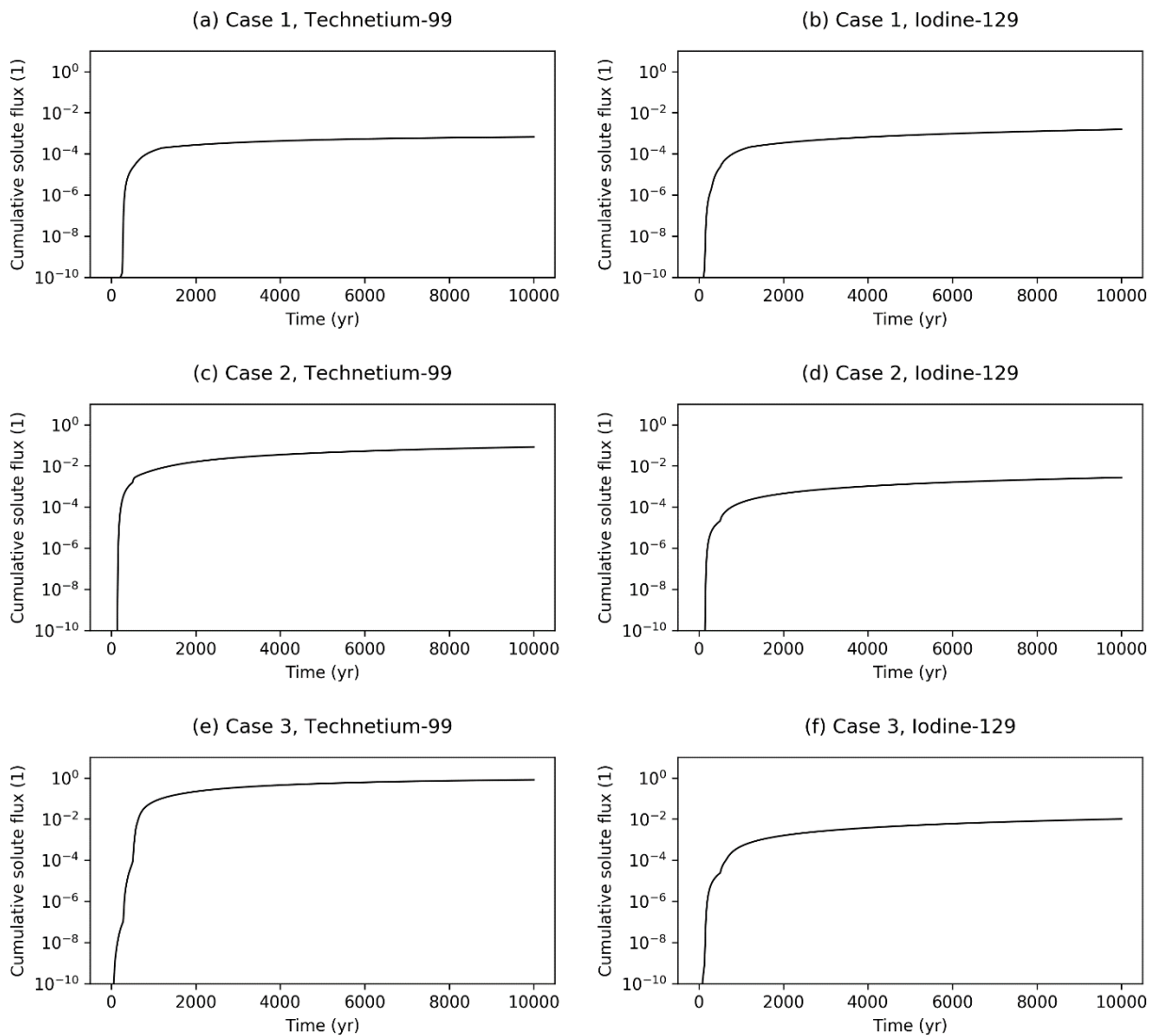


Figure G-11. Cumulative solute release for technetium-99 (left) and iodine-129 (right) for the three waste form systems (Cases 1 – 3).

Preliminary Conclusions

Preliminary results demonstrate that it is important to consider risks to groundwater holistically, by examining waste form release rates on an individual and system basis. This was an important result for the ILAW glass system, but conclusions cannot yet be drawn because simulations and their corresponding analyses are still on-going. This includes exploring key parameter bounding estimates impacting solute transport and subsequent risks to groundwater. Although the solute flux can be used a surrogate for determining relative risks, actual risks need to be determined using groundwater concentrations. In a subsequent report revision, results will be updated with bounding parameter estimates impacting waste form release behavior, longer-term solute fluxes for glass, solute fluxes from steam reformed product, and risk calculations that are based on solute transport from the IDF to the groundwater table.

G.5 WASTE CONTROL SPECIALISTS

G.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 material⁹⁹, and (3) the **Federal Waste Disposal Facility (FWF)**. Figure G-2 is an aerial photograph of the disposal facilities for radioactive wastes at WCS. The remainder of this subsection will focus exclusively on the FWF, which was designed, licensed, and constructed for "federal waste" disposal, including all wastes from the DOE.

G.5.1.1 Physical Setting

The area surrounding 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 WCS facility is underlain by 600-foot (185-m) thick red-bed clays, which are ten times less permeable than concrete. Importantly, the facility is not over a drinking water aquifer or adjacent to any underground drinking water supply.¹⁰⁰ The lack of a groundwater pathway has a positive influence on the WAC as discussed in Section G.5.4.1.

G.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.

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 G-3 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

⁹⁹ 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).

¹⁰⁰ Much of this information is from the WCS website at <http://www.wcstexas.com/about-wcs/environment/>

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.

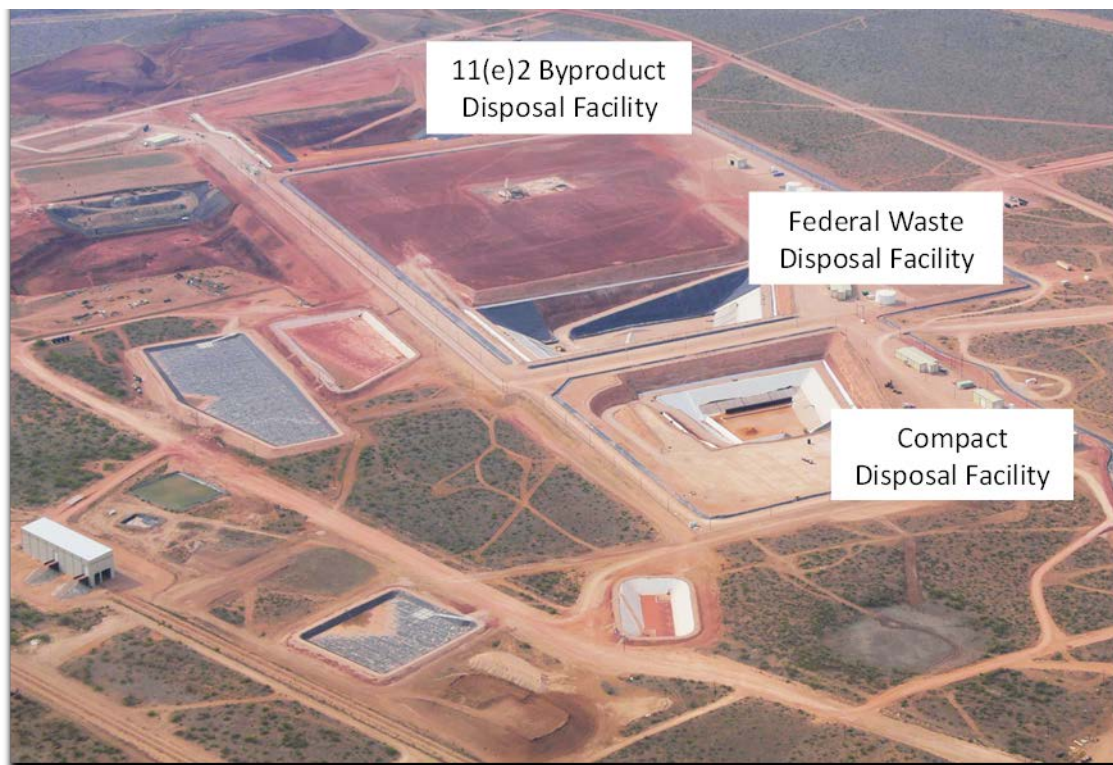


Figure G-2 Aerial View of Radioactive Waste Disposal Facilities at WCS



Figure G-3 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 on site from nearby Eunice, New Mexico.

G.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 II 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 G-2.

The term of the current license is through September 2024, with provision for 10-year renewals thereafter. The state of Texas takes ownership of 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 off-site 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/>.

G.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.

G.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.

G.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 K.

G.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 G-7 for long-lived nuclides and Table G-8 for short lived nuclides.

Table G-7 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 G-8 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.

G.5.4 Classification of Wasteforms for Disposal

Table I and Table II (reproduced as Tables G-7 and G-8) 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.

G.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 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 II 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 II 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 II wastes will cause the concentrations of all nuclides to be higher than the concentrations from Grout Case II, with its larger volume increase (factor of 1.8). For these two reasons, the Steam Reformed Case II wastes will have a higher classification than the Grout Case II WFs.

G.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 G-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 G-2) 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 that 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 will also be 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 will be Class C.

G.5.4.3 Classifying the Primary Wasteforms Using WCS's 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 wastes are produced by the WTP-PT and the LAWPS. Table G-9 presents the list of primary WFs being considered for disposal at the WCS FWF.

Table G-9 Nature and Volume of Primary WFs for Disposed at WCS.

	Container	Total Volume	Average Volume per month	Containers per month (337 months)
Grout Case II with LDR pretreatment (2g2)	8.4 m ³ bag in reusable steel overpack	367,900 m ³	1092 m ³	130
Grout with LDR pretreatment & 99% Sr-90 removed (2f)	8.4 m ³ bag in reusable steel overpack	367,900 m ³	1092 m ³	130
Steam Reforming Case II (3b)	8.4 m ³ bag in reusable steel overpack	245,300 m ³	728 m ³	87

The Feed Vector data is contained in a large EXCEL Spreadsheet discussed in Section 2.2 and G.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 facilities¹⁰¹. The results of this categorization is presented in Table G-10.

Table G-10 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 II with LDR pretreat (2g2)	0	408	33	0
Grout with LDR pretreat & 99% Sr-90 removed (2f)	406	2	33	0
Steam Reforming Case II (3b)	0	302	130	9

The clear majority of the primary Grout Case II 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 II 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 II 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).

¹⁰¹If 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.

Nine months of feed from the WTP-PT, when immobilized by Steam Reforming Case II, 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 G-11 presents detailed information on the nine months in which the Steam Reformed Case II mineral product would be classified as GTCC. If the sum of fractions from WCS's Table 1 Radiological WAC (Table G-7) 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 G-11 presents an analysis in which Feed from the WTP-PT and LAWPS, for a given month, are combined prior to immobilization; and the last column of Table G-11 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 G-11 clearly demonstrates that local mixing can be used to prevent the generation of GTCC LLW.*

Table G-11 Calculation of Volume-Weighted, Table 1, Sum-of-Fractions for Steam Reformed Case II.

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

G.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 significant 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 on-site 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 off-site disposal at WCS as **Pretreatment Waste (PW)**.

The volume and curie content of the solidified LSW and SSW are summarized in Table G-12 below. These volumes and curie contents are developed in Section G.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 G-12 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 will be carried into the cost analysis for disposal and Appendix H (Off-Site Transportation). Table G-15 summarizes information on the solidified LSW to be further assessed.

Pretreatment Waste - In option 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 in a grout waste form. 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 A₂ quantity per box. The A₂ quantity and shipping as low-specific activity material are discussed in detail in Appendix H. Table G-13 shows the limiting Class C limit for disposal at WCS and the limiting A₂ value for a volume of 2.5 m³ (discussed in detail in Appendix H).

Table G-13 Limiting Criteria for Shipping and Disposal of Tc-99 and I-129 (assuming 2.5 m³ shipping container).

	A₂ value for shipping	WCS Class C limit for disposal
Tc-99	24 Ci	3 Ci/m ³
I-129	unlimited	0.08 Ci/m ³

As shown in Table G-13, 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 G-14 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 G-14 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/m ³	3,890 m ³	4,280 m ³	13 m ³
I-129	11.92	0.08 Ci/m ³	150 m ³	165 m ³	0.5 m ³

Because of the very small volume of PW containing I-129, only the volume of solidified PW containing Tc-99 will be carried into the cost analysis for disposal and the off-site transportation analysis. *Table G-15 presented the volumes and classification of all Secondary Wastes to be carried forward for disposal costing and for off-site transportation analysis in Appendix H.*

Table G-15 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 (1c is primary cannister Vit to IDF & secondary to WCS)	3,803 m ³	Class A	12 m ³	5
Pretreatment Waste containing Tc-99 (from 2e2)	4,280 m ³	Class C	13 m ³	5

G.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 off-site 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 disposal of MLLW at WCS are presented in a 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 will use:

- \$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 on-site disposal activities such as verifying paperwork, radiological surveying and unloading the waste packages from the railcar.

As shown in Table G-16, the disposal fees were used to calculate the disposal costs for Grout Case II, Steam Reformed Case II, the solidified LSW from Vitrification and the PW from variant 2e2. The disposal costs shown in Table G-16 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 G-16 Disposal Costs for Disposal of Grout Case II, Steam Reformed Case II, Solidified LSW from Vitrification and Pretreatment Waste Containing Tc-99.

Waste Form	Total Volume	Class A	Class B	Class C	Disposal Costs
Grout Case II with LDR pretreat (2g2)	367,900 m3	0	408 months	33 months	\$1.9 B*
Steam Reformed Case II (3b)	245,300 m3	0	302 months	139 months	\$1.3 B*
Solidified LSW from Vit (from 1c)	3,803 m3	3,803 m3	0	0	\$0.0052 B
Pretreatment Waste containing Tc-99 (from 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)					

G.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 G-17.

Table G-17 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 G-17, 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 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 dispose¹⁰² 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).

G.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 II and Steam Reforming Case II and all analyzed secondary WFs) can be accepted for disposal at the WCS disposal facility (assuming LDR issues are addressed).

¹⁰² 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 H. EXPANDED DISCUSSION – TRANSPORTATION CONSIDERATIONS

H.1 INTRODUCTION

This appendix describes the programs that will be needed to transport the primary Grout Case II and Steam Reformed Case II wasteforms (WFs) and secondary WF 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.

H.2 GENERAL EVALUATION ASSUMPTIONS AND APPROACH

For this analysis, current conditions are assumed to prevail. This means that the analysis is based on the current railroads, the current regulatory requirements for shipping and the current shipping and packaging technologies.

Basing the analyses on current conditions prevents undue speculation about future conditions, while allowing an even-handed comparison of disposal of 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.

H.3 KEY REGULATORY CONSIDERATIONS

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*.

H.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),¹⁰³ materials may be shipped in industrial packages (IPs) that are exempt from NRC package certification (but not exempt from DOT requirements)

¹⁰³ 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 “A₂” content limit¹⁰⁴, must be shipped in Type A packaging, and where
- Higher-activity content materials that exceed the LSA limits, and that exceed the A₂ 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 index¹⁰⁵ 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.

H.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 A₂ limit are presented in Appendix A of 10 CFR 71.

H.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 A₂ quantity. The three types of LSA materials and requirements that IPS must meet are discussed in detail in Section H.7.

H.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

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).

¹⁰⁴ The A₂ 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)

¹⁰⁵ 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 requirements above will be captured, without summarizing the large number of safety requirements found in 49 CFR 171-173 for shipping radioactive materials. The NRC and DOT requirements for shipping LSA materials are detailed in Section 7.6.

H.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.

H.3.5 National Environmental Policy Act

Actual implementation of a large-scale, off-site disposal program, with the associated transportation program, such as outlined here in Appendix H, 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 H.10.

H.4 NATURE AND VOLUME OF WASTES TO BE SHIPPED

The nature and volume of the wastes to shipped are described in Appendix G, “Expanded Discussion—Disposal Site Considerations,” and are summarized in Table H-1 below. As discussed in Appendix G, the primary waste forms 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 H-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 II with LDR pretreatment (2g2)	8.4 m3 bag in reusable steel overpack	367,900 m3 and 1092 m3/month	130
Grout with LDR pretreatment & 99% Sr-90 removed (2f)	8.4 m3 bag in reusable steel overpack	367,900 m3 and 1092 m3/month	130
Steam Reforming Case II (3b)	8.4 m3 bag in reusable steel overpack	245,300 m3 and 728 m3/month	87
Secondary Wastes			
Solidified Liquid Secondary Wastes from Vit (1c is primary cannister Vit to IDF & secondary to WCS)	B-25 box	3,803 m3 and 12 m3/month	5
Pretreatment Waste containing Tc-99 (from 2e2)	B-25 box	4,280 m3 and 13 m3/month	6

H.5 LAG STORAGE FACILITY

Figure H-1 shows the variability in the number of containers of immobilized waste produced per month—from essentially no output in one month to over 250 8.4 m3 containers of grout in the next month. To even out the high and low production months shown in Figure H-1, a “lag storage facility” will be built at the immobilization facility so that a constant volume of waste can be shipped and disposed. Shipping a constant volume each month over many years is cost effective, allowing uniform staffing, equipment and shipping capacity.

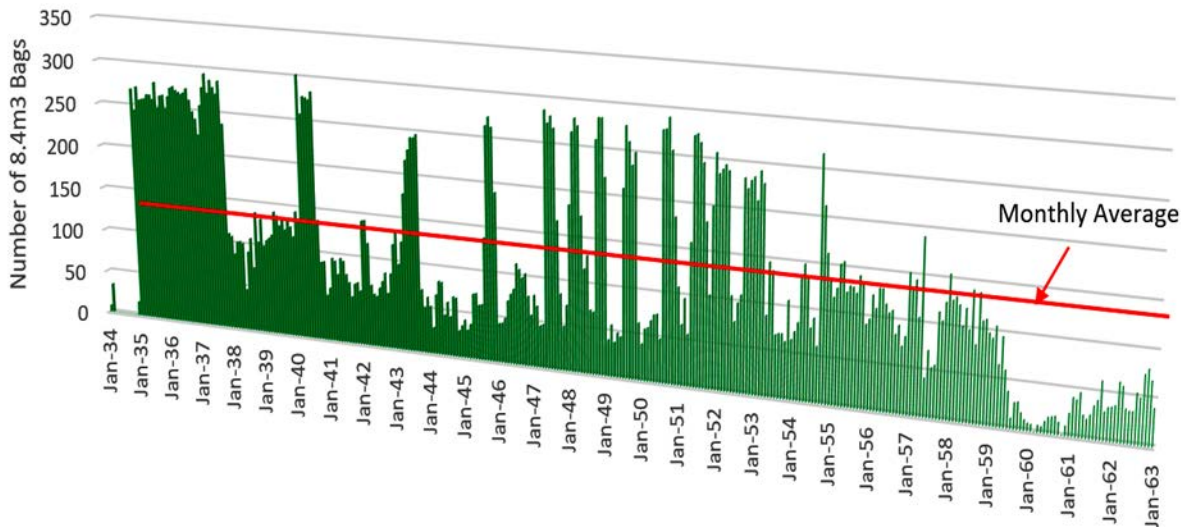


Figure H-1. Number of 8.4 m3 Containers of Grout Produced per Month

As shown in Figure H-1, the average number of 8.4 m3 containers of grout produced each month will be 130 containers. Therefore, the simplest shipping program is to ship 130 containers of grout each month. As discussed in Section H-8, 26 railroad gondolas per month will be required to ship 130 8.4 m3 containers of grout. If more than 130 containers of waste are produced in a month, the excess is sent to lag storage, and if fewer than 130 containers are produced in one month, the shortfall is pulled from lag storage. A spreadsheet was set up to determine the number of 8.4 m3 containers of grout in lag storage at any point in time, based on shipping 26 gondolas of packaged grout each month. As shown in Figure H-2, the lag storage facility for grout will need to have a capacity of ~6000 containers



Figure H-2. Number of 8.4 m3 Containers of Grout in Lag Storage based on shipping 36 gondola rail cars (130 containers) per month

To reduce the size of the lag storage facility, two other shipping scenarios were considered. Scenario 1 is based on doubling the shipping program to 52 gondolas (260 containers) of grout per month for the first few years, then dropping to the long-term average of 26 gondolas per month (see Figure H-3). Scenario 2 is based on the use of four shipping rates: 0, 13, 26 and 52 gondola railcars of waste per month (see Figure H-4). The number of containers of waste in lag storage based on these two scenarios is plotted below in Figure H-5. [many thanks to Elena Kalina of Sandia National Laboratories for the analysis presented in this section]

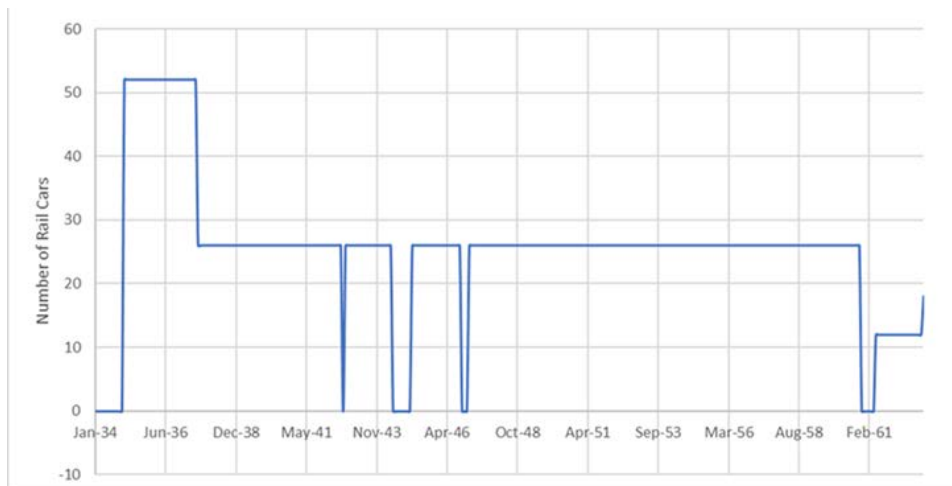


Figure H-3. Scenario 1 – Number of Gondola Rail Cars of Grout Shipped per Month

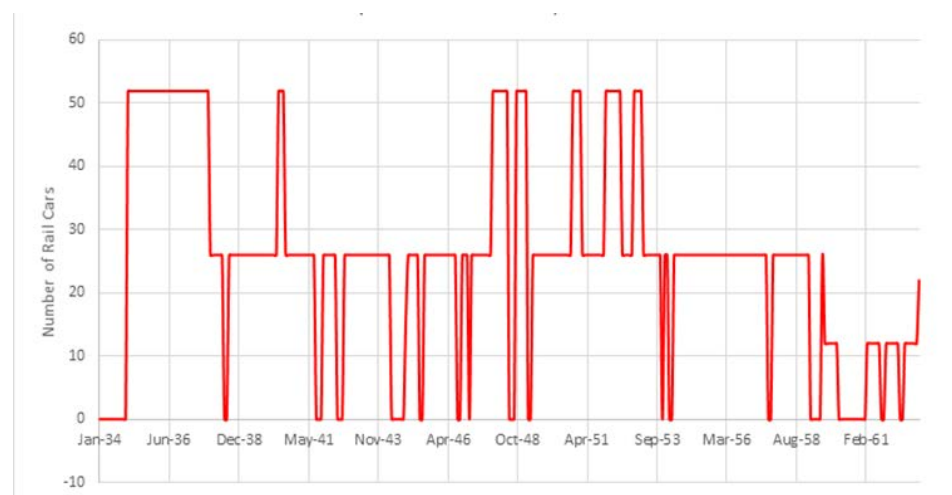


Figure H-4. Scenario 2 – Number of Gondola Rail Cars of Grout Shipped per Month

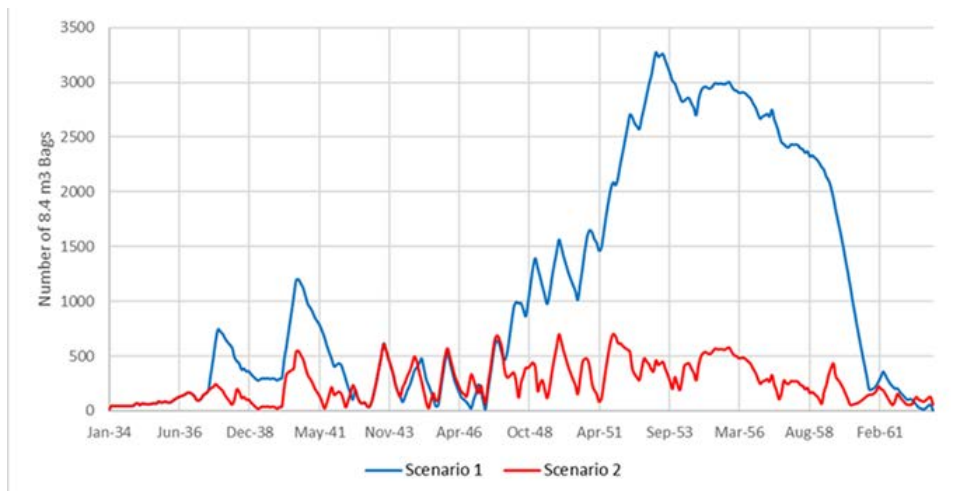


Figure H-5. Number 8.4 m3 Grout Containers in Lag Storage Based Scenario 1 and Scenario 2

The capacity of a lag storage facility for the Steam Reformed Case II WF can be derived by multiplying the numbers of 8.4 m3 containers in each figure by 0.67 (= volume multiplier 1.2 for steam divided by 1.8 for grout).

H.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 $10^{-4} A_2/\text{gram}$ for solids** and gases, and $10^{-5} A_2/\text{gram}$ for liquids

LSA-III includes solids (e.g., consolidated wastes, activated materials), *excluding powders*, that 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 $2 \times 10^{-3} A_2/\text{gram}$** .” (10 CFR 71.4)

Other criteria 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 CFR 71.14(b)(3)(i)) and 49 CFR 173.427).

Calculating the A₂ Value for a Mixture of Radionuclides

The A₂ 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 A₂ for a mixture of radionuclides is presented in Figure H-3, which is copied from the NRC's Appendix A of 10 CFR 71.

$$A_2 \text{ for mixture} = \frac{1}{\sum_i \frac{f(i)}{A_2(i)}}$$

where f(i) is the fraction of activity for radionuclide I in the mixture, and A₂(i) is the appropriate A₂ value for radionuclide I.

Figure H-6. Formula for Calculating the A₂ for a Mixture of Radionuclides

As a potentially bounding assessment of the A₂ value of 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 waste forms for disposal at WCS, it was determined that SLAW from the WTP PT for November 2035 had the very highest sum of fractions. The A₂ calculation for wastes from November 2035 is presented in Table H-2.

Note in Table H-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 G contains a table that presents the *average radiological content* of all the combined SLAW from the WTP-PT and LAWPS for the 28 years of operations. As shown in the table in Appendix G, 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 H-2. A₂ 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

Symbol	Element	A ₂ (Ci) from Apx A 10 CFR 71	Concentration (Ci/m ³) from Feed Vector	fraction contribution f(i)	f(i)/A ₂ (i)
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
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

Symbol	Element	A ₂ (Ci) from Apx A 10 CFR 71	Concentration (Ci/m ³) from Feed Vector	fraction contribution f(i)	f(i)/A ₂ (i)
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/m ³ =	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 A₂ 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 A₂ is 8.29E-02 curies and there are 0.54 curies in each m³. With the A₂ value, it is possible to determine if a specific WF meets the concentration limits for shipping as an LSA material.

Classifying the Grout Waste Form as LSA-III

The criteria for LSA-III specifically mentions concrete WFs, and the Grout Case II 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 criteria for specific activity, 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 H-2). With an activity multiplier of 0.56 (=1/1.8) for Grout Case II and a specific density of 1770 kg/m³ (see Appendix G), the specific activity of the Grout Case II is 1.2E-06 Ci/gram (= (4.07 x 0.56) / 1770,000).

For the SLAW from the WTP PT for November 2035, the A₂ is 0.597 (Table H-2) and the LSA-III criteria is 2×10^{-3} of the A₂/gram or 1.19E-03 Ci/gram. **Therefore, the specific activity of the Grout Case II 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 II 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 II 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.
- The radioactivity is essentially uniformly distributed in a solid compact binding agent (such as concrete, bitumen, ceramic, etc. Because of the process of mixing the liquid SLAW with the dry ingredients, the Grout Case II 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 A₂. 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 will be conducted to validate this assumption.

Classifying the Steam Reformed Case II Granular Waste Form as LSA-II

The criteria for LSA-III specifically excludes “powders,” which excludes the steam reformed granular mineral product from being classified as LSA-III. However, the Steam Reformed Case II 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. This analysis focuses on the criteria for specific activity, and other criteria are discussed qualitatively. Note that the specific activity criteria for LSA-II is an order of magnitude stricter ($< 10^{-4}$ A₂/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 H-2). With a curie multiplier of 0.83 ($=1/1.2$) for the Steam Reformed Case II granular WF, and a specific density of 800 kg/m³ (see Appendix G), the specific activity of the Steam Reformed Case II granular WF is 4.2E-06 Ci/gram ($= (4.07 \times 0.83) / 800,000$). For the SLAW from the WTP PT for November 2035, the A₂ is 0.597 (Table H-1) and 10^{-4} of the A₂/gram is 5.97E-05 Ci/gram. **Therefore, the specific activity of the Steam Reformed Case II 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 concentrations of all 47 nuclides tracked in the Feed Vector, and the Steam Reformed Case II WF using these parameters 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 II WFs can be shipped at LSA-II material.

Other criteria for LSA-II:

- External radiation on the external surface of the shipping package must not exceed 2 mSv/h (200 mrem/h) and 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. Because of the self-shielding, and because the steamer reformed waste form 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 waste form would meet both dose-based criteria. If additional funding were available, Microshield calculations could be done in the future to confirm this assumption.
- The radioactivity is essentially uniformly distributed. Because of the immobilization process in the fluidized steam bed, the Steam Reformed WF will meet this criteria.

H.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 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 Type IP-2 packages, which in turn must meet the *general design requirements* of 49 CFR 173.410, and when subjected to the *tests specified in 49 CFR 173.465 (c) (free drop test) and (d) (stacking test)* must prevent the (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 H-7 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 H-7. Example of Soft Side Container for Shipping LSA Materials
(photograph from PacTec, Inc literature¹⁰⁶)

Reusable Steel Overpacks for Shipping

To facilitate handling, to increase public confidence 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 H-8, but lighter weight and with a shallower lid. Finally, Figure H-9 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.

¹⁰⁶ <https://www.pactecinc.com/products/llmw-flexible-packaging>



Figure H-8. Example of a Reusable Steel Split-Cavity Overpack (actual overpack could be smaller, and with shallower lid) (photograph from Container Technologies Industries, LLC literature¹⁰⁷)



Figure H-9. Example of B-25 Box
(photograph from Container Technologies Industries, LLC literature)

H.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

¹⁰⁷ <http://www.containertechologies.com/>

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.

H.8 ROUTING AND PROGRAM TO TRANSPORT WASTE TO WCS BY RAIL

All wastes will be shipped on gondola railcars. Table H-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 H-4 summarizes the number of gondola railcars needed each month to transport the average monthly amount of each WF.

Table H-3. Calculating Number Containers per Gondola Railcar Based on 200,000 Pound Cargo Limit

	Specific Weight Waste Form	Container Size	Weight per Container + 10%	Containers per Gondola
Primary Wastes				
Grout Case II with LDR pretreatment (2g2)	1770 kg/m3 (110 lb/ft3)	8.4 m3	16,350 kg ~ 36,000 lb	5
Grout with LDR pretreatment & 99% Sr-90 removed (2f)	1770 kg/m3 (110 lb/ft3)	8.4 m3	16,350 kg ~ 36,000 lb	5
Steam Reforming Case II (3b)	800 kg/m3 (50 lb/ft3)	8.4 m3	7,392 kg 16,260 lb	12
Secondary Wastes				
Solidified Liquid Secondary Wastes from Vit (1c 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 (from 2e2)	1770 kg/m3 (110 lb/ft3)	2.5 m3	4,868 kg 10,700 lb	18

Table H-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 II 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 II (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
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To summarized Table H-4, the transportation of the Grout 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 month with 78 gondola rail cars (Grout) or 24 gondola railcars (Steam Reformed) could improve efficiency.

Routing

The map of rail routes (Figure H-10) shows two primary routes, southward through Californian and then eastward across the desert Southwest, or southeastward from Richland. The latter rout was chosen, as it is somewhat more direct, and goes through states with lower population densities. The rail route show in Figure H-10 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 sent their locomotive the short distance to Eunice, NM to bring the railcars to their facilities in Tx. The total distance is 2232 mi. The calculated travel time by dedicated train is 79 hours (3.3 days). H-

The route includes 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.

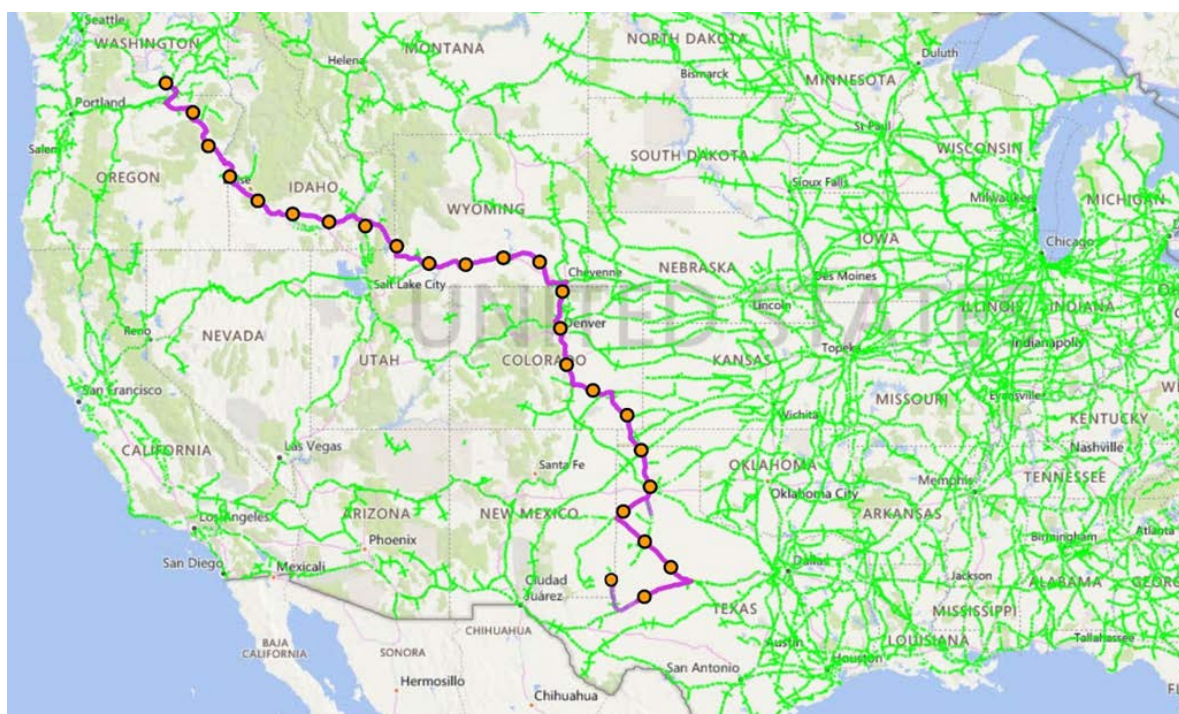


Figure H-10. Rail Routes and the Selected Dedicated Train Rail Route

H.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.

Table H-5. Railroad Cost to Ship Primary Wasteforms from Richland to WCS

Waste Form	Average number railcars per month	Total Cost for 337 months
Grout Case II with LDR pretreatment (2g2) ¹⁰⁸	26	\$0.136 B
Steam Reforming Case II (3b)	8	\$0.042 B

H.10 TECHNICAL RISKS

H.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:

- **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.

¹⁰⁸ 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

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 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) the mode (truck or rail), (7) possible accident scenarios for those waste forms, and (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>).

H.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 H-6 summarizes key parameters for this NDAA study and those selected from the WVDP EIS.

Table H-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, Table D-1)
Type of Wastes	MLLW	LLW and MLLW
Number of railcars, Grout Case II	312 (1 years of grout at 26 railcars per month)	615 (all LLW+ MLLW, Alternative A, Table D-3)
Number of railcars, Steam Reformed Case II	96 (1 years of Steam Reformed at 8 railcars per month)	615 (all LLW+ MLLW, Alternative A, Table D-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 transportation distance and a scaling for the number of railcars. The translation factors are detailed as footnotes to entries in Table H-7.

Table H-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 Grout 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)					

The scaled statistical number of non-radiological rail traffic fatalities range from 0.75 to 2.4 for the summed 28 years of shipping SLAW.

The WVDP EIS transportation analysis is based on rail accident rates compiled 20 years ago in 1999 (page D-11 of the WV EIS). To increase confidence in this scaled analysis, current DOE statistics for rail 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 760 fatalities per year 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 741 million Train-miles per year based on a 11-year average from 2006 through 2016 (inclusive).

Combining the statistics, there were an average of 1.0 fatality 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 Grout Case II were shipped every 3 months (78 gondola railcars per train, instead of 26), the statistically number of fatalities, for the 28-year program, would drop to 0.50 fatalities. To put this impact in context; 28 years of rail operations will result in 21,280 statistical fatalities.

H.11 PROGRAMMATIC RISKS

This NDAA 3134 Study completed a semH-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 off-site transportation program: Political opposition, in major city on rail route, following rail accident, causes DOE to temporarily stop shipping.

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.

H.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, 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).

H.13 CONCLUSIONS

The key take-away from this detailed analysis is that the primary WFs (Grout Case II and Steam Reforming Case II) 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 as low specific activity material, the NRC's least hazardous category of material. 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 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 railcars (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.

APPENDIX I. EXPANDED DISCUSSION: SELECTION OF CASES

I.1 SUMMARY

The FFRDC team met on May 1 -3, 2018 to perform a comparative analysis of the approaches being considered by the team for treatment of the Supplemental LAW. This analysis was performed to develop consensus on the treatment approaches that the team should evaluate and identify gaps in information at that point in the investigation.

Twenty-two potential approaches using vitrification, grouting, and steam reforming as the primary treatment technology were identified by the FFRCD team, and twelve options were evaluated as shown in Table I-1. The remaining ten options were not evaluated because the team felt that they were bounded by the twelve cases listed in Table I-1. The five best representative cases selected for detailed evaluation also are highlighted in Table I-1.

Table I-1. Evaluated Approaches for Supplemental Treatment of Low-Activity Waste

5 Best Representative Cases (not in rank order)	12 Options Evaluated (not in rank order)	Score* (H/M/L)
1	VITRIFICATION CASE 1 - Vitrification - primary & secondary waste to IDF (1)	L
	1c – Vitrification - primary waste to IDF, secondary waste to WCS (1c)	M
	1d - Bulk vitrification- primary & secondary waste to IDF (1d)	L
	1g - Bulk vitrification in large container - primary waste to IDF, secondary waste to WCS (1g)	M
	2 - Grout - primary & secondary waste to IDF (2)	M
2	GROUT CASE 1 - Grout with LDR pretreatment - primary & secondary waste to IDF (2d)	M
	Grout with LDR and Tc & I pretreatment - primary & secondary waste to IDF, Tc & I to HLVT (2e1)	M
	Grout with LDR and Tc & I pretreatment - primary & secondary waste to IDF, Tc & I to WCS (2e2)	M
	Grout with LDR and Sr pretreatment - primary waste to WCS, secondary waste to IDF, Sr to HLVT (2f)	H
3	GROUT CASE 2 - Grout with LDR pretreatment - primary waste to WCS, secondary waste to IDF (2g2)	H
4	STEAM REFORMING CASE 1 - Steam reforming - primary & secondary waste to IDF (3)	L
5	STEAM REFORMING CASE 2 - Steam reforming - primary waste to WCS, secondary waste to WCS (3b)	H

*H = High, M = Medium, L = Low

The options to treat supplemental LAW waste by vitrification and steam reforming with both primary and secondary waste disposal at IDF received low scores. The scores for these treatment technologies improved when options for disposal of either the primary or secondary waste form at WCS instead of IDF was considered. The option to treat supplemental LAW by grouting without pretreatment with both primary and secondary

waste disposal at IDF received a moderate score. Pretreating and grouting supplemental LAW for disposal at WCS improved the scores for the grouting treatment technology.

A sensitivity analysis was performed to understand how the selection of criteria weighting factors impacted the ranking results. Changing the weighting factors over a wide range of values had little to no impact of the relative rankings of the treatment options shown in Table I-1.

The results from this analysis were used to help focus the evaluations performed by the FFRDC team in this study. It was also used in the development of mitigation approaches to reduce risks as described in Section 3.0, “Analysis Risk Assessment.”

I.2 EVALUATION METHODOLOGY

The options analysis was performed using the Analytical Hierarchy Process (AHP) decision-modeling method developed at the Wharton School of Business at the University of Pennsylvania. This model provides a structured framework that allows ranking of both qualitative and quantitative selection criteria defined by the team of subject matter experts.¹⁰⁹

The FFRDC team identified criteria for evaluating the options and metrics to measure how well each option could meet the selection criteria. The relative importance of the selection criteria and metrics was determined using pairwise comparisons (for example, how does one weight “cost” as a criterion relative to “schedule”?). This approach provides decision makers with the ability to focus solely on the two decision criteria/metrics being evaluated in isolation, without the distraction or complicating effects of other criteria. The pairwise process generated weighting factors for each individual criterion and metric. A relative weighting factor was then developed for each metric by multiplying the weighting factor for the metric by the weighting factor for the associated criterion.

Five ratings were used to determine how well an option satisfies a metric: 5-Strong, 4-Moderate/Strong, 3-Moderate, 2-Low, 1-None. Definitions were developed by the FFRDC team for the ratings for each metric. Each option was assigned a rating between 1 and 5 for each metric. The ratings were made by the FFRDC team based on experience and guided by the metric definitions. Weighted ratings for the metrics were obtained by multiplying the ratings by the appropriate relative weights of the metrics. An overall score for an option was obtained by summing the weighted ratings.

I.3 EVALUATION OF OPTIONS

Twenty-two approaches, summarized in Table I-2, were identified by the FFRDC team for consideration in the evaluation process. The evaluation team determined that 10 of the approaches would be adequately bound by the other 12 approaches and would not warrant further evaluation. The remaining 12 approaches are described in Table I-3 and were assessed using the AHP methodology. Vitrification with disposal at IDF is the present plan of record and was used as a baseline for comparison.

Each approach was assigned a rating between 1 and 5 for each metric by the FFRDC team based on their experience and guided by the metric definitions (See Table I-4). Weighted ratings for the metrics were obtained by multiplying the ratings by the appropriate relative weights of the metrics. An overall score for an approach was obtained by summing the weighted ratings. The results are shown in Table I-1.

¹⁰⁹ Thomas L. Saaty, “A Scaling Method for Priorities in Hierarchical Structures,” *Journal of Mathematical Psychology*, 15: 234–281, 1977.

A sensitivity analysis was performed to understand the impacts of the weighting factors on the various evaluation criteria. Each approach was evaluated using equal weighting factors for the 10 criteria (i.e., 10% each). Five additional criteria weighting factor schemes were evaluated for comparison to the team-generated weighting factors. In each scheme, each criterion was given a weighting factor ranging from 30% to 70%, and the remaining amount required to make 100% was equally divided among the other nine criteria.

Table I-2. Approaches Considered for Evaluation

Option Title	Evaluated?
1 – Vitrification – primary & secondary waste to IDF	Yes
1a – Vitrification - primary waste to WCS, secondary waste to IDF	No
1b – Vitrification - primary waste to WCS, secondary waste to WCS	No
1c – Vitrification - primary waste to IDF, secondary waste to WCS	Yes
1d - Bulk vitrification – primary waste in large container & secondary waste to IDF	Yes
1e - Bulk Vitrification - primary waste in large container to WCS, secondary to IDF	No
1f - Bulk Vitrification - primary waste in large container to WCS, secondary to WCS	No
1g - Bulk Vitrification - primary waste in large container to IDF, secondary to WCS	Yes
2 - Grout – primary & secondary waste to IDF	Yes
2a - Grout– primary waste to WCS, secondary to IDF	No
2b - Grout– primary waste to WCS, secondary to WCS	No
2c- Gout – primary waste to IDF, secondary to WCS	No
2d - Grout with LDR pretreatment - primary & secondary waste to IDF	Yes
2e1 - Grout with LDR and Tc & I pretreatment - primary & secondary waste to IDF, Tc & I to HLVT	Yes
2e2 - Grout with LDR and Tc & I pretreatment - primary & secondary waste to IDF, Tc & I to WCS	Yes
2f - Grout with LDR and Sr pretreatment - primary waste to WCS, secondary waste to IDF, Sr to HLVT	Yes
2g1 - Grout with LDR pretreatment - primary waste to WCS in B-25 box, secondary waste to IDF	No
2g2 - Grout with LDR pretreatment - primary waste to WCS in large container, secondary waste to IDF	Yes
3 - Steam Reforming – primary & secondary waste to IDF	Yes
3a - Steam Reforming - primary waste to WCS, secondary waste to IDF	No
3b - Steam Reforming - primary waste to WCS, secondary waste to WCS	Yes
3c - Steam Reforming – primary waste to IDF, secondary to WCS	No

Major observations from the options analysis include:

- Using the team’s criteria weighting factors, the approaches for pretreating supplemental LAW (for LDR and/or Sr) and grouting for disposal at WCS received high overall scores. Steam reforming for disposal at WCS also received a high score. Vitrification, bulk vitrification, and steam reforming for disposal at IDF received low scores. Grouting (with or without pretreatment) for disposal at IDF and vitrification with secondary waste disposal at WCS ranked in the middle.
- When the 10 criteria were assigned equal weights (10% each), the relative ranking of the approaches did not change significantly from the ranking obtained from using the team’s criteria weighting factors.

- Changing the weighting factor for each criterion from 30% to 70% did not significantly change the relative rankings. Minor changes in the rankings were noted when safety and primary waste form compliance received high (>50%) weightings.
 - When safety was weighted much higher than all other criteria, grout for disposal at IDF moved up in the ranking and grout and steam reforming for disposal at WCS began to have ratings closer to those of the vitrification and steam reforming treatment options with disposal at IDF.
 - When primary waste form compliance was weighted much higher than all other criteria, vitrification for disposal at IDF moved up in the ranking, but it did not rank as high as grout or steam reforming waste forms disposed of at WCS.

Table I-3. Description of Treatment Options Evaluated

Option Title	Attributes	Assumptions	Pathways
1 - Vitrification	Primary Waste Disposition: IDF Primary Container: LAW Canister Pretreatment: None Pretreatment Waste Disposition: N/A Scrubber liquid, etc: LERF/ETF Secondary Solid Waste Disposition: IDF	Four additional melters - same as LAW melters, Glass formulation from System Plan 8; idling is not considered but will increase size; secondary waste stays on site	Supplemental LAW feed vector -> Vit plant near WTP, SLAW waste pumped to Feed Tank, Melter Feed prep tank, Melter feed tank, melter, Container filling, Container Decon, Lag Storage Facility, Disposal at IDF; SBS concentrate, HEME and scrubber got to EMF for evaporation; bottoms are recycled, overheads sent to LERF/ETF
1c - Vit to IDF, Secondary to WCS	Primary Waste Disposition: IDF Primary Container: LAW Canister Pretreatment: None Pretreatment Waste Disposition: N/A Scrubber liquid, etc: LERF/ETF Secondary Solid Waste Disposition: WCS	Same conditions as Vitrification case but with primary to IDF, secondary to WCS	
1d - Bulk Vitrification	Primary Waste Disposition: IDF Primary Container: 44 MT container Pretreatment: None Pretreatment Waste Disposition: N/A Scrubber liquid, etc: LERF/ETF Secondary Solid Waste: IDF	Two 44 MT melters; secondary waste stays on site;	Supplemental LAW feed vector -> Vit plant near WTP, SLAW waste pumped to Feed Tank, Waste drier, Dried waste handling system, melter, Bulk Vit Container (44MT) filling, Container Decon, Lag Storage Facility, Disposal at IDF; SBS concentrate, HEME and scrubber go to LERF/ETF
1g - Bulk vit in large container to IDF, Secondary to WCS	Primary Waste Disposition: IDF Primary Container: Large (10 m ³) Container Pretreatment: None Pretreatment Waste Disposition: N/A Secondary Solid Waste Disposition: WCS	Two 44 MT melters; secondary waste goes off-site;	
2 - Grout	Primary Waste Disposition: IDF Primary Container: 8.4m ³ bag in box Pretreatment: None Pretreatment Waste Disposition: N/A Secondary Solid Waste Disposition: IDF	Hanford Cast Stone Mixture, Volume increase is assumed to be 1.8, no pretreatment beyond WTP-PT/LAWPS; all equipment will be contact handleable	Supplemental LAW feed vector -> Grout plant near WTP, SLAW waste pumped to Feed Tank, Batch mixer, Container filling, Container Decon, Lag Storage Facility, Disposal at IDF
2d - Grout with LDR pretreatment, Primary & Secondary waste to IDF	Primary Waste Disposition: IDF Primary Container: 8.4m ³ bag in box Pretreatment: LDR Pretreatment Waste Disposition: N/A Secondary Solid Waste Disposition: IDF	Grout base case with pretreatment for LDR, Primary to IDF, Secondary to IDF	

Table I-3. Description of Treatment Options Evaluated Continued

Option Title	Attributes	Assumptions	Pathways
2e1 - Grout with LDR and Tc & I Pretreatment to HLViT Primary & Secondary waste to IDF	Primary Waste Disposition: IDF Primary Container: 8.4m3 bag in box Pretreatment: LDR, Tc, I Pretreatment Waste Disposition: Tc, I to HLViT Secondary Solid Waste Disposition: IDF	Grout base case with pretreatment for LDR, Tc, I sent to HLViT, Secondary to IDF	See Case 2
2e2 - Grout with LDR and Tc & I Pretreatment to WCS Primary & Secondary waste to IDF	Primary Waste Disposition: IDF Primary Container: 8.4m3 bag in box Pretreatment: LDR, Tc, I Pretreatment Waste Disposition: Tc, I to WCS Secondary Solid Waste Disposition: IDF	Grout base case with pretreatment for LDR, Tc, I grouted and sent to WCS, Secondary to IDF	See Case 2
2f - Grout with LDR and Sr pretreatment; Primary waste to WCS	Primary Waste Disposition: WCS Primary Container: 8.4m3 bag in box Pretreatment: LDR, Sr Pretreatment Waste Disposition: Sr to HLViT Secondary Solid Waste Disposition: IDF	Grout base case with pretreatment for LDR, Sr to HLViT, Secondary to IDF	See Case 2
2g2 - Grout with LDR pretreatment; Primary waste to WCS	Primary Waste Disposition: WCS Primary Container: 8.4m3 bag in box Pretreatment: LDR Pretreatment Waste Disposition: N/A Secondary Solid Waste Disposition: IDF	Grout base case with pretreatment for LDR; grouted secondary to IDF	See Case 2
3 - Steam Reforming	Primary Waste Disposition: IDF Primary Container: 8.4m ³ Pretreatment: None Pretreatment Waste Disposition: N/A Secondary Solid Waste Disposition: IDF	Two complete FBSR systems, Grout or geopolymer monolith system to encapsulate the granular product before storage, Caustic scrub goes back to FBSR system	Supplemental LAW feed vector -> FBSR plant near WTP, SLAW waste pumped to Feed Tank, Waste Staging tank, FBSR system, waste product handling system, Container filling, Lag Storage Facility, Disposal at IDF; off-gas system (Thermal oxidation, Carbon bed for Hg, Caustic scrub for I, HEPA)
3b - Steam Reforming to WCS, Secondary to WCS	Primary Waste Disposition: WCS Primary Container: 8.4m3 Pretreatment: None Pretreatment Waste Disposition: N/A Secondary Solid Waste Disposition: WCS	Not macroencapsulated in containers to WCS. Dried, packaged SSW to WCS	See Case 3

Table I-4. Definitions of Criteria and Metrics

Criteria	Metric	Metric Weighting (%)	Metric Definition	Metric Bin Descriptions		
				5 - Strongly	3 - Moderate	1 - None
Technical Maturity and Process Simplicity & Reliability	TRL	0.4	Assessment of the TRL levels for all unit operations based on EM TRL Guide. (Note: Expert judgement was used when formal TRL values were not available)	TRL is judged to be 7 or greater	TRL is judged to be 4 or 6	TRL is judged to be 3 or less
	Maturation of TRL	1.9	Assessment of ability to mature the technology to TRL 7 within schedule and budget constraints (includes risks)	Technology can be readily matured to TRL 7 within schedule and budget constraints	Technology can be matured to TRL 7, but not within schedule and budget constraints	Unlikely that technology can achieve TRL 7 within an acceptable timeframe/cost
	Number of Unit operations	0.8	Assessment of the number of major unit operations required by the option	Low number of unit operations	Moderate number of unit operations	High number of unit operations
	Simplicity of Feed Start-up/shut down	1.3	Assessment of the complexity of starting or stopping the processing of waste including consideration for downstream impacts	Simple and short start-up/shutdown operations	Moderate start-up/shutdown operations	Complex and long start-up/shutdown operations
	Simplicity of control of unit operations	1.3	Measure of the overall complexity of controlling the entire waste form production process. Number of parameters that must be controlled/monitored.	Minimal number of controls and low level of operator interaction relative to other options	Moderate number of controls and level of operator interaction relative to other options	Large number of controls and high level of operator interaction relative to other options
Safety	Nuclear and Radiological Hazards	2	Addresses the number and magnitude of nuclear and radiological hazards and the engineering and administrative controls required	Few hazards require controls; few controls are active controls	Moderate hazards require controls; moderate number of controls are active controls	Significant active controls or new hazards
	Chemical Hazards	1.1	Addresses the number and magnitude chemical hazards and the engineering and administrative controls required	Few hazards require controls; few controls are active controls	Moderate hazards require controls; moderate number of controls are active controls	Significant active controls or new hazards
	Physical Hazards	0.6	Addresses the number and magnitude physical hazards (e.g. thermal, rotating equipment, etc.) and the engineering and administrative controls required	Few hazards require controls; few controls are active controls	Moderate hazards require controls; moderate number of controls are active controls	Significant active controls or new hazards
	Transportation Hazards	1.1	Potential for accidents, On-site vs off-site, miles traveled, number of shipments	Low shipment miles	Moderate shipment miles	Large number of shipment miles
Operational Flexibility	Ability to handle range of feed vector compositions	2.6	Measures the ability to solidify the full spectrum of feed vector compositions expected	Solidifies all feed vector compositions. No additional pretreatment is required.	Solidifies most feed vector compositions. Some additional pretreatment is required.	Solidifies some feed vector compositions. Extensive additional pretreatment is required.
	Ability to handle range of feed vector flowrates	1.6	Measures the ability to handle the full spectrum of feed vector flowrates expected. A measure of the turndown ratio of the processes	Handles all feed vector flowrates within existing surge capacity with no upstream/downstream consequences	Handles most feed vector flowrates within existing surge capacity with some upstream/downstream consequences	Handles some feed vector flowrates within existing surge capacity with significant upstream/downstream consequences
	Ability to prevent/rework off-spec product	3.2	Measures the ease of avoiding off-spec product and/or the easy of rework or ability to deal with off-spec product	Easy	Moderate	Very difficult
	Analytical requirements	0.8	The number and complexity of the analytical requirements to support the processing and disposition	Low number of samples/analytes with simple analyses and easily obtained within timeframe required	Moderate number of samples/analytes with simple analyses easily obtained within timeframe required	Large number of samples/analytes with complex analyses which are hard to obtain within timeframe required

Table I-4. Definitions of Criteria and Metrics Continued

Criteria	Metric	Metric Weighting (%)	Metric Definition	Metric Bin Descriptions		
				5 - Strongly	3 - Moderate	1 - None
Economy	Development Cost	1.2	The cost to complete the required R&D to allow the design to be completed	Estimated cost is low relative to other alternatives and uncertainty in cost estimate is low	Estimated cost is moderate relative to other alternatives and/or uncertainty in cost estimate is moderate	Estimated cost is high relative to other alternatives or uncertainty in cost estimate is high
	Capital Cost (includes permits & D&D etc.)	6.4	The cost of design, construction, permits, acceptance tests, start-up operation prior to hot operations, and D&D at end of life. Includes any required additional pretreatment, lag storage, and secondary waste treatment facilities.	Estimated cost is low relative to other alternatives; uncertainty in cost estimate is low	Estimated cost is moderate relative to other alternatives uncertainty in cost estimate is moderate	Estimated cost is high relative to other alternatives; uncertainty in cost estimate is high
	Operational / Annual Cost	4.2	Annual costs for operation, supplies, labor, maintenance, analytical, utilities, pretreatment, treatment, transportation, and waste disposal (primary and secondary)	Estimated cost is low relative to other alternatives and uncertainty in cost estimate is low	Estimated cost is moderate relative to other alternatives and/or uncertainty in cost estimate is moderate	Estimated cost is high relative to other alternatives or uncertainty in cost estimate is high
Schedule ("Speed")	Development time prior to design	2.7	The time to complete the required R&D to TRL 7 to allow the design to be completed	Estimated time to complete the required R&D to support the design is short relative to other alternatives	Estimated time to complete the required R&D to support the design is moderate relative to other alternatives	Estimated time to complete the required R&D to support the design is long relative to other alternatives
	Time to complete design, construction, and hot startup	10.7	The time to design, construct, permit, complete acceptance tests and start-up operation leading to hot operations to support consent decree. Includes time to do the same for any required additional pretreatment and secondary waste treatment facilities.	Estimated time to complete the design, construction and hot start-up is short relative to other alternatives; float is provided to meet consent decree; uncertainty in schedule estimate is low	Estimated time to complete the design, construction and hot start-up is moderate relative to other alternatives; schedule meets consent decree and/or uncertainty in schedule estimate is low	Estimated time to complete the design, construction and hot start-up is long relative to other alternatives; does not consent decree schedule; or uncertainty in schedule estimate is high
Resilience to Changes	Project Resilience	2.5	Resilience to impacts from outside factors such as funding availability, support facilities, etc.	Resilience high compared to other options	Resilience moderate compared to other options	Resilience low compared to other options
	Operational Execution Resilience	1.4	Resilience to impacts during operations by changes in items such as feed vector variability, changes in disposal WAC, raw materials, etc.	Resilience high compared to other options	Resilience moderate compared to other options	Resilience low compared to other options
	TRL Related Resilience	3.5	Measures probability of successful technology maturation. Does not include waste form performance	Probability is high compared to other options	Probability is moderate compared to other options	Probability is low compared to other options
Primary Waste Form Compliance	Compatible with Existing / Draft Disposal Site WAC	18.5	Confidence that process can produce waste form that can meet WAC and performance requirements as they exist today. Existing /draft permit and WAC is the basis.	High confidence that waste form meets all pertinent criteria	Moderate confidence that waste form meets all pertinent criteria	Low confidence that waste form meets all pertinent criteria

Table I-4. Definitions of Criteria and Metrics Continued

Criteria	Metric	Metric Weighting (%)	Metric Definition	Metric Bin Descriptions		
				5 - Strongly	3 - Moderate	1 - None
Secondary Waste	Quantity	2.8	Volume of secondary waste produced	Low relative to other alternatives	Moderate relative to other alternatives	High relative to other alternatives
	Compatible with Existing / Draft Disposal Site WAC	8.3	Confidence that process can produce waste form that can meet WAC and performance requirements. This assumes that the existing IDF permit will be modified to accept the limited quantity of secondary waste (i.e. failed equipment, HEPA filters, etc)	High confidence that waste form meets all pertinent criteria	Moderate confidence that waste form meets all pertinent criteria	Low confidence that waste form meets all pertinent criteria
Regulatory Considerations	Permitting/licensing complexity for new facilities & processes	4.9	Confidence that defensible permit applications for construction and operation of processing facilities can be prepared, i. e. NEPA, CAA, CWA, DOE regulations, etc.	A strong technical basis exists to support completion of permit applications and high confidence that applications will can be submitted in timeframe to support mission	A moderate technical basis exists to support completion of permit applications and moderate confidence that applications will can be submitted in timeframe to support mission	A limited technical basis exists to support completion of permit applications and low confidence that applications will can be submitted in timeframe to support mission
	Compliance with shipping regulations	1.8	Confidence that shipping regulations can be met	High confidence that packaging and shipping requirements can be met	Medium confidence that packaging and shipping requirements can be met	Low confidence that packaging and shipping requirements can be met
	Permitting/licensing complexity for disposal	8.9	Confidence that defensible permit applications can be prepared for disposal of primary and secondary waste forms, i. e. NEPA, CWA, DOE regulations	A strong technical basis exists to support the timely completion of permit applications and high confidence that applications will support mission. Minor permit modifications required for option's final waste forms	A moderate technical basis exists to support the timely completion of permit applications and moderate confidence that applications will support mission. Moderate permit modifications required for option's final waste forms	A limited technical basis exists to support the timely completion of permit applications and low confidence that applications will support mission. Significant permit modifications required for option's final waste forms
End State Decommissioning	Complexity (includes residual inventory)	2.6	Complexity to deactivate and D&D the facility	Easy and quick to support task relative to other alternatives	Moderate complexity and time requirement to support task relative to other alternatives	Hard and lengthy to support task relative to other alternatives
	Waste Volume	0.9	Volume of waste produced in the deactivation and D&D of the facility	Low relative to other alternatives	Moderate relative to other alternatives	High relative to other alternatives

APPENDIX J. EXPANDED DISCUSSION: COST ESTIMATE METHODOLOGY AND RESULTS

J.1 SUMMARY

This appendix presents preliminary capital and life-cycle costs for the base cases of each Supplemental Low Activity Waste (SLAW) technology and is considered a Class 5, Business Decision Estimate Range (BDER) based on the criteria found in the Association for the Advancement of Cost Engineering, International (AACEI), recommended practices.

J.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%.

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.

J.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 Liquid Waste Staging Building *[Bates: What is this?]*
- 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.

J.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.

J.5 ESTIMATE EXCLUSIONS

Assumes non-consumable installed equipment will last the life time of the project.

Estimate Flow Sheets

Flow sheets 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 utilized and the following analog facilities were identified for use in the process of estimating.

J.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 Supplemental LAW 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.

J.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 Supplemental LAW grout. It is a good analog, but significant handling, pretreatment (for variants), and logistical unit operations must be included.

J.5.3 Fluidized Bed Steam Reforming (FBSR)

Integrated Waste Treatment Unit (IWTU) at the Idaho Site.

IWTU is nominally half the capacity required for Supplemental LAW fluidized bed steam reforming, and will produce a different mineral (aluminosilicate versus sodium carbonate) 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.

J.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 also noted there is more deviation between certain analogs and the projected Supplemental LAW process. Adjustments were made to reflect significant increases in unit operations or complexity, or reductions in same. Further, 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 (*minimum for all options*)
2. WTP SLAW Vitrification Facility with 4 melters and off gas 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) melters and off gas 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 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.

High scope for this process assumes the need to remove Technetium (Tc) and Iodine (I). Other options are being developed including pretreatment for organics and ammonia, as required.

Another variant evaluated was construction of the grout plant at IDF.

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 130,000 gallons
3. Installation of cryogenic nitrogen and oxygen tanks
4. Balance of Facilities, as required
5. Lab Storage and Shipping Facility

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.

J.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 flow sheets 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.

J.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.

- Hot start 2033
- Full operations in 2036
- Operations through 2061

Decommission and Deactivation will proceed when authorized. Duration will be dependent on final state of the facilities impacted.

J. 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 reporting and current ORP System Planning values, which also appear to rely on the updated WTP project costs. The project TPC cost for SLAW vitrification is considerable. It is noted that 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) 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 is 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. 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 (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 multi-decade program.

**Preliminary Summation of Base Scope Cost Numbers
Base and Variant Scopes Combined**

Vitrification Technology

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost*
\$340M – \$1560M	\$1,000M – \$2,600M	\$680M – \$15,600M	\$1M – \$2.6M	\$10,080M – \$12,810M	N/A	\$10,000M – \$14, 625M	\$1,421M – \$1,536M	\$27,000M – \$52,000M

Fluid Bed Steam Reforming Technology Base Case Scope

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost*
\$480M – \$1,100M	\$1,000M – \$2,600M	\$1,900M – \$6,880M	\$1M – \$2.6M	\$2,520M – \$4,914M	\$1,850M – \$2,775M	\$300M – \$690M	\$1,421M – \$1,536M	\$8,000M – \$19,000M

Cast Stone Technology Base Case Scope

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost*
\$90M – \$280M	N/A	\$500M – \$2,180M	\$1M – \$2.6M	\$1,120M – \$1,680M	\$2,775M – \$4,163M	\$250M – \$2,258M	\$142M – \$193M	\$2,100M – \$10,000M

- Total Program Cost is rounded.

NOTE: COSTS REQUIRE UPDATE. SEE TABLE 2 IN EXECUTIVE SUMMARY.

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)

Variant Case Scope – Next Generation Melters

Waste concentrate feed tank with a capacity of 500,000 gallons
Design of new vitrification facility and support systems for the following key systems
Melter feed system capable of receipt and handling of treated waste
Glass forming chemical handling and blending system
Glass Forming Chemical Silos (5)
Two (2) next generation melters (NGM)
Two (2) off-gas trains (primary and secondary systems)
Effluent Management Facility (EMF) and support systems
Effluent Treatment Facility (ETF) and support systems
Glass container handling and decontamination facility and support systems; bulk vitrification containers 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)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost
\$340M – \$1,020M	\$1,000M – \$2,600M	\$6,800M – \$15,600M	\$1M – \$2.6M	\$10,080M – \$15,120M	N/A	\$560M – \$1,600M	\$1,536M	\$29,757M – \$51,478M

Variant Case – Next Generation Melters

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost
\$680M – \$1,560M	\$1,000M – \$2,600M	\$6,800M – \$15,600M	\$1M – \$2.6M	\$8,540M – \$12,810M	N/A	\$420M – \$1,200M	\$1,421M	\$18,862M – \$49,218M

NOTE: COSTS REQUIRE UPDATE. SEE TABLE 2 IN EXECUTIVE SUMMARY.

Estimate Basis

Estimate range is -30% to +100%, assuming FY18 costs and overheads, with no escalation applied for Technology Development, Pilot Plant, Total Project Cost (TPC), and IDF Expansion

Technology development is driven by current rate of R&D expenditure and expected lessons learned from WTP-LAW

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

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 \$360M per year for base case and \$305M per year for Variant Case with a +50% estimate range

Major Equipment Replacement driven by number of melter replacements (24 base/12 variant) and has a -30% to +50% estimate range.

Decommissioning & Demolition costs are 5% of TPC and OPEX costs high range costs

Work Breakdown Structure, Basis and Cost Breakdown for Fluid Bed Steam Reforming Technology

Base Case Scope

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)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost
\$480M – \$1,100M	\$1,000M – \$2,600M	\$1,900M – \$4,390M	\$1M – \$2.6M	\$3,276M – \$4,914M	N/A	\$300M – \$690M	\$1,536M	\$8,493M – \$15,232M

Variant Case – Granular Product to WCS

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost
\$480M – \$1,100M	\$1,000M – \$2,600M	\$1,900M – \$6,880M	N/A	\$2,520M – \$3,780M	\$1,850M – \$2,775M	\$300M – \$690M	\$1,421M	\$9,471M – \$19,246M

NOTE: COSTS REQUIRE UPDATE. SEE TABLE 2 IN EXECUTIVE SUMMARY.

Estimate Basis

Estimate range is -30% to +100%, assuming FY18 costs and overheads, with no escalation applied for Technology Development, Pilot Plant, Total Project Cost (TPC), and IDF Expansion

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 \$117M per year for base case and \$90M per year for variant case 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; 245,300 m³ 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 m³ 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

Decommissioning & Demolition costs reflected are assumed to be the same as Vitrification Technology for comparison purposes

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 1 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)

Base Case 2 Scope – Grout at IDF

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
Pretreatment facility to remove organics and metals to comply with Land Disposal Restrictions (LDR) with support systems
Tanks, pumps, resin beds, filters, etc.
Double jacketed pipeline to Integrated Disposal Facility (IDF)
Large Disposal Units (LDU) at IDF

**Work Breakdown Structure, Basis and Cost Breakdown for
Cast Stone Technology (continued)
Base Case**

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost
\$90M – \$210M	N/A	\$500M – \$1,150M	\$1M – \$2.6M	\$1,120M – \$1,680M	N/A	\$250M – \$1,160M	\$142M	\$2,103M – \$4,944M

Variant Case 1 – Grout Pre-Treatment

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost
\$120M – \$280M	N/A	\$650M – \$1,464M	\$1M – \$2.6M	\$1,120M – \$1,680M	\$2,775M – \$4,163M	\$320M – \$1,508M	\$157M	\$5,143M – \$9,854M

Variant Case 2 – Grout at IDF

Technology Development	Pilot Plant TPC & OPEX	Total Project Cost (TPC)	IDF Expansion	OPEX/Life Cycle Cost	Shipment WCS	Major Equipment Replacement	D&D	Total Program Cost
\$90M – \$210M	N/A	\$950M – \$2,180M	\$1M – \$2.6M	\$1,120M – \$1,680M	N/A	\$820M – \$2,258M	\$193M	\$3,174M – \$6,523M

NOTE: COSTS REQUIRE UPDATE. SEE TABLE 2 IN EXECUTIVE SUMMARY.

Work Breakdown Structure, Basis and Cost Breakdown for Cast Stone Technology (continued)

Estimate Basis

Estimate range is -30% to +100%, assuming FY18 costs and overheads, with no escalation applied for Technology Development, Total Project Cost (TPC), and IDF Expansion

Technology development lower because of no 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 m³ 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 m³ 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

Major Equipment Replacement for Variant 3 includes cost for Variant 2 plus and additional \$125M for four Large Disposal Units (LDU).

Decommissioning & Demolition costs are 5% of TPC and OPEX costs high range costs

Acronyms

AACEI	Association for the Advancement of Cost Engineering, International
AoA	Analysis of Alternatives
BDER	Business Decision Estimate Range
EAC	Estimate at Completion
OPC	Other Project Costs
PRD	Program Requirement Document
ROM	Rough Order of Magnitude
TEC	Total Estimated Cost

APPENDIX K. EXPANDED DISCUSSION – REGULATORY COMPLIANCE

K.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) radioactive waste management activities as prescribed under various DOE orders, including DOE Order 435.1 (DOE O 435.1), "Radioactive Waste Management".¹¹⁰ 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 waste¹¹¹ (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 components¹¹² (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 on-site or off-site 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

¹¹⁰ DOE Order 435.1 governs the management of radioactive waste at DOE sites, including criteria for wastes that are not considered high-level.

¹¹¹ 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.

¹¹² 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.

K.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.¹¹³ 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 address criterion 1. Criterion 3 is addressed principally through the LAW processing to ultimately produce a LAW waste form, either through WTP LAW vitrification, or through supplemental LAW 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 waste form and the disposal site considerations. Disposal sites demonstrate compliance with criteria 2 by developing performance assessment analyses, considering both the inventory of radionuclides, waste forms, 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 waste form performance data and analysis available.

K.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

¹¹³ 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.

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 SSTs and 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 K-1 for the characteristic hazardous wastes, Table K-2 for listed hazardous wastes, and Table K-3 for WA State-only waste classifications, below.¹¹⁴ These codes are identified in the RCRA Part A issued by Ecology for both the single-shell tanks (SSTs) and the double-shell tanks (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. 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,

¹¹⁴ RPP-8402, Rev.1., DRAFT, Integrated Disposal Facility Waste Acceptance Criteria, 2005.

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 K-1 Federal and State RCRA Characteristic Hazardous Waste Codes Applicable to the 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

Table K-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.)

Table K-3 WA State-only Waste Codes 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)

K.4 LAND DISPOSAL REQUIREMENTS APPLICABLE TO HANFORD WASTE

Under RCRA, Hanford tank waste is categorized as non-wastewater and radioactive mixed waste subject to Land Disposal Restriction (LDR).¹¹⁵ The tanks are considered a storage area for multiple upstream points of generation where the waste was originally produced.¹¹⁶ The LDR program (established under 40 CFR Part 268) requires 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 (BDAT) that reduces the toxicity and mobility of the hazardous waste.¹¹⁷

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 [Need a TPA or other reference] 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. 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

¹¹⁵ 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.

¹¹⁶ Winston, T.A., 2013. HLVIT Applicability to Supplemental Immobilization: Impact of a RCRA New Point of Generation. RPP-RPT-52699, Rev.0.

¹¹⁷ EPA, 2005. Introduction to Land Disposal Restrictions (40 CR Part 268). EPA530-K-013.

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 years¹¹⁸. 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 Site.

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 waste forms 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 include 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 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.¹¹⁹ 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. Appendix G lists all applicable LDR standards for Hanford tank waste.

¹¹⁸ A no-migration petition is not technically credible for on-site Hanford disposal where there is a direct pathway to groundwater. However, for an appropriate off-site disposal location, such as WCS, a no-migration petition may be technically credible.

¹¹⁹ 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).

[Placeholder for the RCRA flowchart figure, a graphics editor may be able to create a nice flowchart based on our excel sheet]

K.5 REQUIREMENTS FOR AIR EMISSIONS

For the processing of the low 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.

K.6 WASTE FORM PERFORMANCE REQUIREMENTS

Waste form 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. Chapter 6 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. The rest of this section on IDF will move to Chapter 6.

Table K-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 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		

			Total Waste Standards	Waste Extract Standards	Technology 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		
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
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

			Total Waste Standards	Waste Extract Standards	Technology Standards	
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 Trichlorophenol	95-95-4	0.18 and meet 268.48 standards	7.4 and meet 268.48 standards	N/A	N/A
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		NA	No numerical or concentration standard	No numerical or concentration standard		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
Hazardous Waste						
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						
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		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
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		
Trichloromethane		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		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
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		
1,4-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		
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-Methylcholanthrene		56-49-5	0.0055	15		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
4-Bromophenylphenyl ether		101-55-3	0.055	15		
4-Chloro-3-methylphenol		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)perylene		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		
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		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
Bromomethane		74-83-9	0.11	15		
Butylbenzyl phthalate		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-1,3-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		
Fluorene		86-73-7	0.059	3.4		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
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-nitrosodi-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-		41903-57-5	0.000063	0.001		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
dioxin (2,3,7,8-)						
Thallium		7440-28-0	1.4	0.20 mg/l TCLP		
trans-1,3-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-Ethoxyethanol 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

K.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 L. HIGH-LEVEL COMPARISON OF THE FIVE PRIMARY CASES

The table below presents a high-level comparison of the five best representative cases of the three technologies specified in the NDAA17 in regard to the attributes specified in NDAA17. Schedule durations reflect the number of years needed before facility hot start-up. Costs are full life-cycle costs, which include project construction, operations, transport, and deactivation and decommissioning.

COST

Vitrification was estimated to be approximately twice the cost of steam reforming and 4-10X the cost for grout. One reason for the higher cost for thermal treatment options was the extensive offgas treatment systems required to ensure stack emissions meet regulatory standards. However, it was noted that a melter is much more expensive than a grout mixer, thus the higher estimated cost was not simply the result of the increased engineering controls. In addition, the annual operating cost for thermal processes was expected to be higher than grout even if offsite disposal costs are considered. Thus, the thermal treatment options were determined to be more expensive to build as well as more expensive to operate than grout.

SCHEDULE

The schedule required to build a vitrification or steam reforming facility is expected to be significantly longer than a grout facility. The overall size and complexity of the facility for the thermal treatment options is much larger than a similar capacity grout plant, driving both cost and schedule.

BENEFITS

Grout 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. Grout was determined to be the least complex option, operates at approximately ambient temperature, and has the fewest controls of the three options. These led to the conclusions that grouting would be the most robust options from a processing standpoint. 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 waste form.

Vitrification results in the lowest primary waste volume and would be able to utilize experience from “first” LAW. Both thermal processes would be expected to destroy any organics and most nitrate in the feed.

REGULATORY COMPLIANCE

A performance assessment has indicated that all waste forms will meet applicable DOE requirements for disposal from a radiological perspective and all three technologies are expected to meet disposal requirements for the RCRA metals in the waste. Vitrification and steam reforming are thermal processes expected to destroy the nitrate and any organics in the waste feed and these components are not expected to be in the immobilized waste while pretreatment to destroy the organic species may be required for grout. It is believed that acceptable pre-treatment processes are available to perform this treatment, but this requirement adds technology development and complexity to the grout option.

TECHNICAL RISK/OBSTACLES

Steam reforming was deemed the least mature and highest technology development risk while grout will require development of a pretreatment process for treatment of LDR organics. Vitrification is the most mature from a technology development standpoint, but was considered the most complex and was considered to have the highest risk for meeting the throughput targets.

PROGRAMMATIC RISKS

Both steam reforming and grout have a programmatic risk of stakeholder acceptance for disposal at IDF. This programmatic risk is minimized if disposal at WCS is selected and disposal at WCS could represent a mitigation step if disposal at IDF is chosen as the preferred site. The high capital cost of vitrification represents a high programmatic risk.

NDA PARAMETERS	VITRIFICATION	GROUT CASE I: DISPOSAL AT IDF	GROUT CASE II: DISPOSAL AT WCS	STEAM REFORMING CASE 1: SOLID MONOLITH PRODUCT TO IDF	STEAM REFORMING CASE 2: GRANULAR PRODUCT TO WCS
SCHEDULE	10-21 Years	8-13 Years	8-13 Years	5-10 Years	5-10 Years
COST	\$27B-\$52B	\$2B – \$5B*	\$5B – \$10B	\$8B – \$15B	\$9B – \$19B
		- Lowest cost option - Schedule comparable to steam reforming but faster than vitrification - Cost and schedule estimates informed by SRS Saltstone operation		- Lowest cost thermal 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 because it is the most similar full-scale process.	
BENEFITS	- Current baseline - Technically mature - Thermal RCRA LDR organic/nitrate destruction - Lowest primary waste volume	- Most compatible integration with WTP - Non-thermal process - Less off-gas - Start/stop flexibility - Worker safety - Least-complex process of three options - Lowest secondary waste volume - Minimal off-gas treatment - No liquid secondary waste stream	- Most compatible integration with WTP - Non-thermal process - Less off-gas - Start/stop flexibility - Worker safety - Least-complex process of three options - Lowest secondary waste volume - Minimal off-gas treatment - No liquid secondary waste stream	- Lowest cost thermal LDR organic/ nitrate destruction - Medium primary & secondary waste volume - Tolerant of feed vector variations and to integrated system process upsets that change the feed vector flowrate or compositions - Can ease system integration complexity - Can be started up, shut down, and operated with reduced feed rate - Thermal process meets BDAT requirements similar to vitrification - Destroys hazardous organics - Destroys nitrates and nitrogen oxides (NOx) - Destroys ammonium compounds - Waste form benefits: - According to recent waste tests, can produce a durable waste form - Does not appreciably increase waste volume during treatment - Does not produce any liquid secondary wastes (besides equipment decontamination, etc.)	
REGULATORY COMPLIANCE	- Primary wasteform compliant for onsite disposal (IDF) - Secondary grout wasteform & onsite disposal (IDF) pending	- High likelihood to meet DOE Technical Performance Criteria for onsite disposal (IDF) (e.g., DOE 435.1) based on Cast Stone data - Grouted waste is not currently permitted at IDF - Permitting of grouted secondary wastes needed for vitrification - Onsite disposal of primary grouted wastes will require permitting	- High likelihood to meet DOE Technical Performance Criteria for onsite disposal (IDF) - Secondary solid waste form & onsite disposal (IDF) pending - Grouted waste forms are compliant with offsite transport (Low-Specific-Activity III material) - Grouted waste forms are compliant with off-site disposal at WCS (licensed to accept Class A, B, C low-level waste and low-level mixed waste)	- High likelihood to meet DOE Technical Performance Criteria for onsite disposal (IDF) - Secondary solid waste form & onsite disposal (IDF) pending	Steam reformer waste forms are compliant with offsite transport and with disposal at WCS
RISKS/ OBSTACLES (Technical)	- Most dependent on integrated facility performance (DFLAW, WTP, TF) - Most complex - Highest throughput risk - Highest secondary waste volume (liquid and solid) - Most impacted by feed variability	- Requires (i) additional R&D to confirm retention characteristics of Cast Stone across relevant feed vector compositions and (ii) formal performance assessment (IDF only) - Potential for LDR organics in feed vector (both IDF and WCS) - Only feed wastes without LDR organics to grout process—may require system plan feed adjustments to address organic peaks - Pretreat wastes to destroy/remove LDR organics—may require R&D of process to remove organics without impacting long-term performance of grouted waste form - Need to demonstrate acceptable performance - May require identification and testing of alternative mix components to mitigate uncertainties in future availability (both IDF and WCS)	- May require System Plan feed adjustments or pretreatment to address organic peaks - Highest primary waste volume - Potential for EPA LDR organics in feed vector (both IDF and WCS) - Only feed wastes without LDR organics to grout process—may require system plan feed adjustments to address organic peaks - Pretreat wastes to destroy/remove LDR organics—may require R&D of process to remove organics without impacting long-term performance of grouted waste form - Need to demonstrate acceptable performance - May require identification and testing of alternative mix components to mitigate uncertainties in future availability (both IDF and WCS)	- Need to mature the overall process from Medium to High for this application - Maturation plan needs to include pilot and demonstration-scale testing, modeling, and waste form performance demonstration - Need to better demonstrate waste form performance enable stakeholders to consider if the mineralized product is acceptable	Lowest technical maturity
RISKS/ OBSTACLES (Programmatic)		- Potential lack of stakeholder/regulator acceptance for onsite disposal (IDF only) - Requires significant concurrent line-item & operational funding (all options/processes)	Requires significant concurrent line-item & operational funding (all options/processes)	- Potential lack of stakeholder/ regulator acceptance for onsite disposal (IDF) - Requires significant concurrent line-item and operational funding (>\$1.5B) (applies to all options considered)	Requires significant concurrent line-item and operational funding (>\$1.5B) (applies to all options considered)

ACRONYMS

BDAT	Best Demonstrated Available Technology
DFLAW	Direct Feed Low Activity Waste
DOE	Department of Energy
EPA	Environmental Protection Agency
IDF	Integrated Disposal Facility (Hanford)
INL	Idaho National Laboratory
IWTU	Integrated Waste Treatment Unit (Idaho)
LDR	Land Disposal Restrictions
NDAA	National Defense Authorization Act (2017)
RCRA	Resource Conservation and Recovery Act
R&D	Research and development
SRS	Savannah River Site
TF	Tank Farm
TRL	Technology Readiness Level
WCS	Waste Control Specialists (Texas)
WTP	Waste Treatment and Immobilization Plant (Hanford)

APPENDIX M. EXPANDED DISCUSSION: FEED VECTOR

M.1 SUMMARY

The Hanford Waste Treatment and Immobilization Plant (WTP) is a complex of facilities⁴ 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 glass⁵. A simplified diagram showing the tank farm, WTP, and other facilities required is shown in Figure M-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 Supplemental LAW 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. Supplemental LAW 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.

Green – Existing Facility
 Blue: Construction complete
 Orange: Construction in progress
 Brown – Design in progress
 Red – Future facility

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

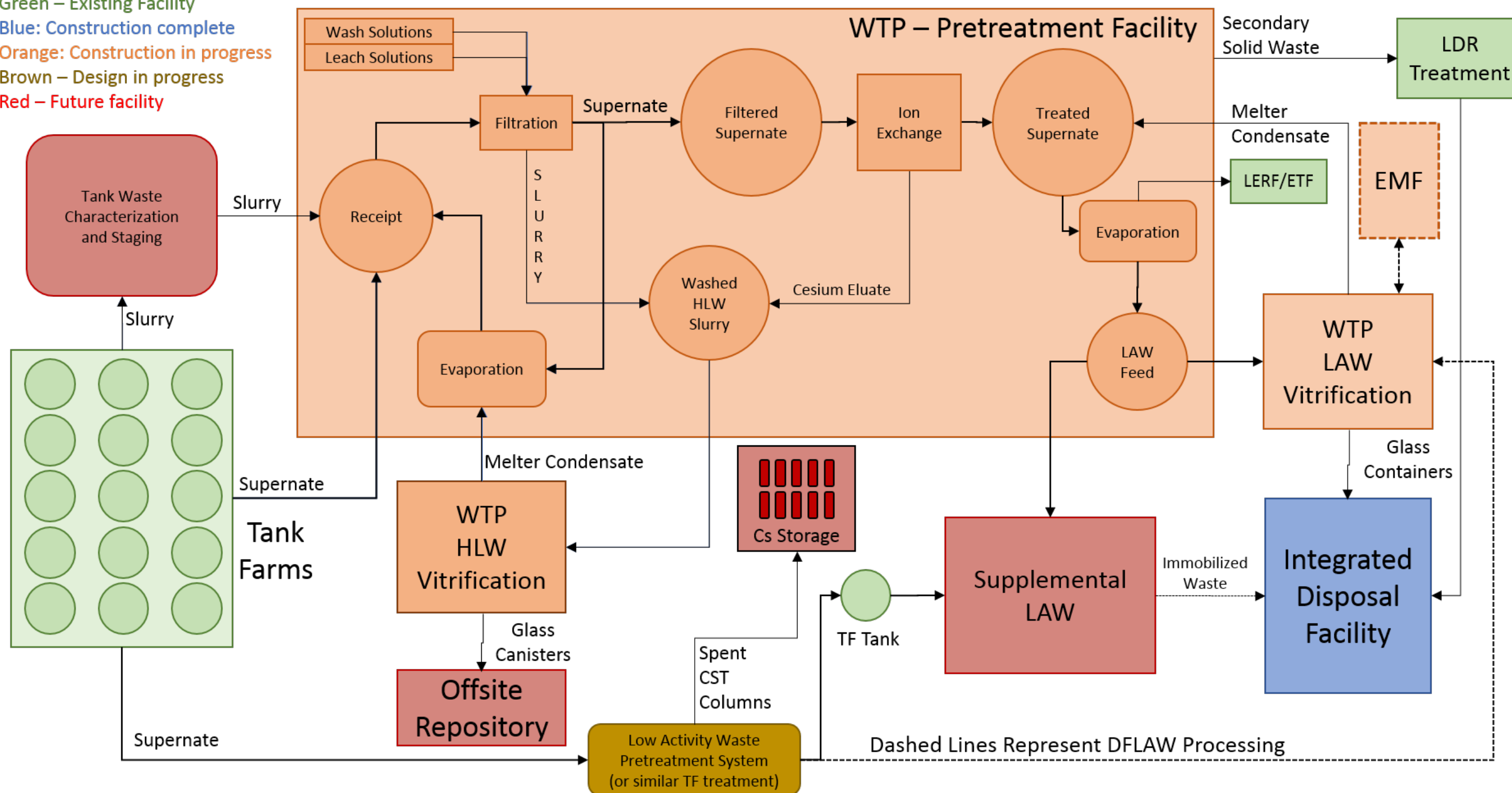


Figure M-1. Simplified Flowsheet for Immobilization of Hanford Waste during Full WTP Operation

M.2 PROCESSES FOR LAW IMMOBILIZATION AND SUPPLEMENTAL LAW IMMOBILIZATION

M.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 storage¹.

The waste has been stored in 177 underground, carbon steel storage tanks. Many of these tanks are known to have developed leaks²; 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 farms³.

M.2.2 Baseline

The Hanford Waste Treatment and Immobilization Plant (WTP) is a complex of facilities⁴ 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 glass⁵.

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 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 Supplemental LAW for immobilization. It is currently estimated that approximately 1/2 of the treated supernate will be sent to Supplemental LAW. 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 Supplemental LAW.

M.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. Other processing options considered in the baseline flowsheet include adding the capability to directly feed the HLW vitrification from the Tank Waste Characterization and Staging Facility⁶.

M.2.3.1 Baseline Supplemental Law Process

A decision on the immobilization technology for Supplemental LAW 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 Supplemental LAW 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 Supplemental LAW facility has two feed vectors in the current baseline flowsheet: Leftover LAW from PT and additional feed from LAWPS⁷. Supplemental LAW 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 Supplemental LAW. Supplemental LAW 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) while solid secondary waste is sent to treatment for land disposal (assumed to be encapsulation in grout with disposal at IDF) at the Land Disposal Restrictions (LDR) treatment facility. The immobilized waste from Supplemental LAW is assumed to be disposed at the IDF, but a final decision has not been made.

The interfaces between Supplemental LAW and other facilities are described in Table M-1 and shown in Figure M-2, based on the assumptions made in the One System Integrated Flowsheet⁶. 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 M-1. Supplemental LAW Interfaces

Stream	Description
45	Treated LAW Feed to Supplemental LAW from PT
46	Treated LAW Feed to Supplemental LAW from LAWPS
47	Stack Exhaust from Supplemental LAW
48	Liquid secondary waste from Supplemental LAW to LERF/ETF

49	Immobilized LAW to IDF
79	Solid secondary waste to a facility to treat waste to permit disposal

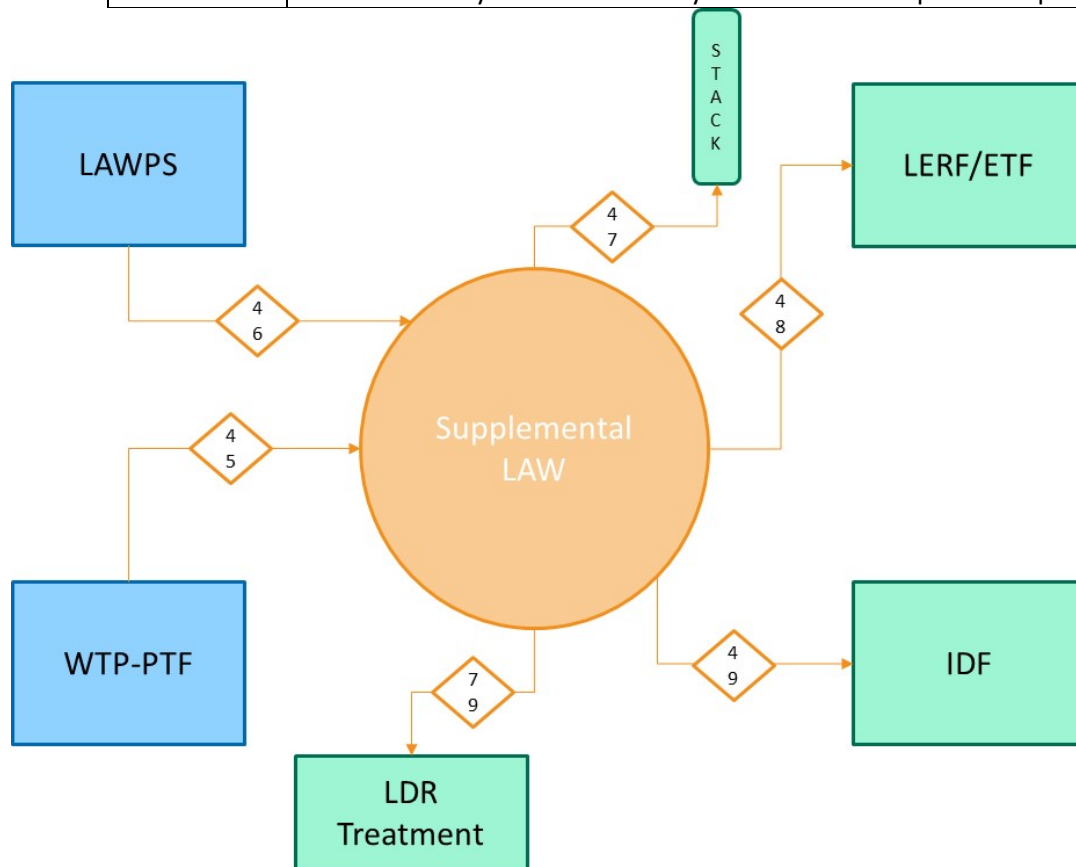


Figure M-2. Supplemental LAW Detail: Interfaces

M.2.3.2 Supplemental Law Feed Vector

The Supplemental LAW feed vector⁷ calculated for the One System River Protection Project Integrated Flowsheet⁶ is being used in the evaluation of the feasibility of proposed Supplemental LAW 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 Supplemental LAW 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 waste form 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 Supplemental LAW feed vector is the best currently available, the actual waste processed through Supplemental LAW could be significantly different than 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 Supplemental LAW facility, as shown in Figure M-3, Figure M-4, Figure M-5, and Figure M-6. Thus, any Supplemental LAW 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 Supplemental LAW 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 facility⁶ from PT in the Integrated Flowsheet.

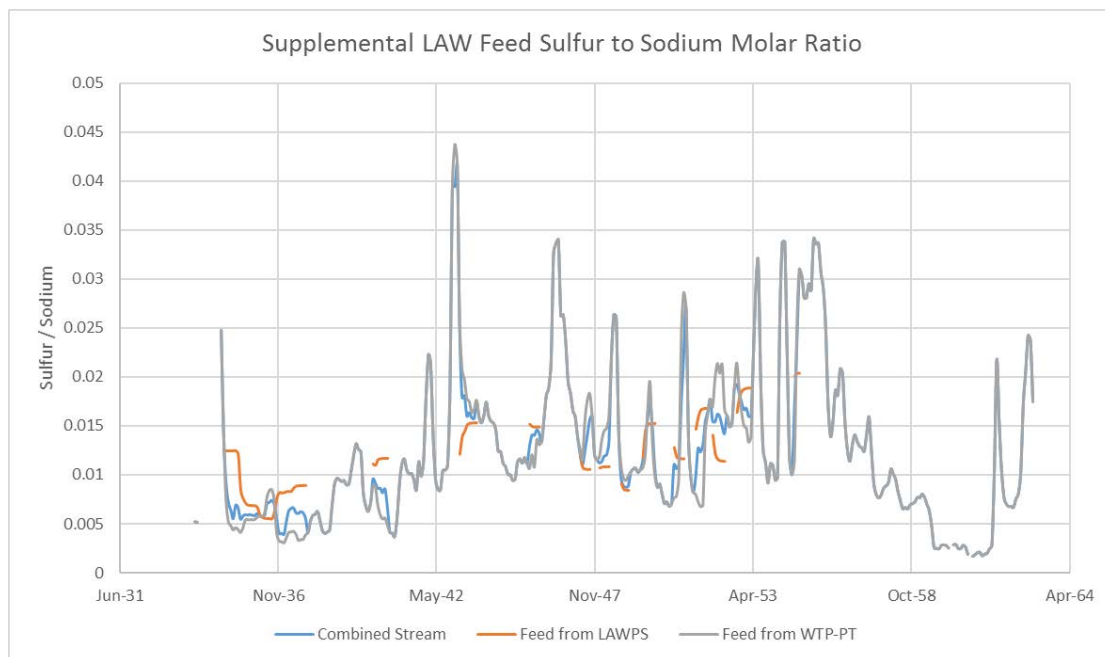


Figure M-3. Sulfur to Sodium Ratio

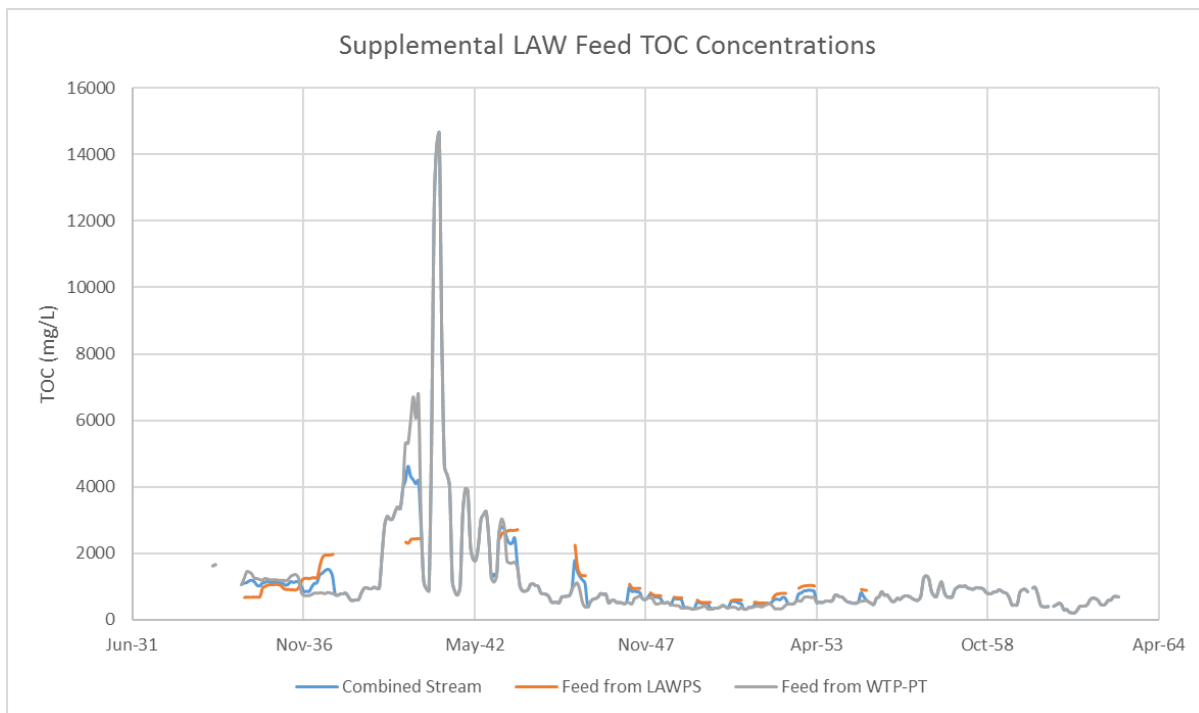


Figure M-4. TOC Concentration

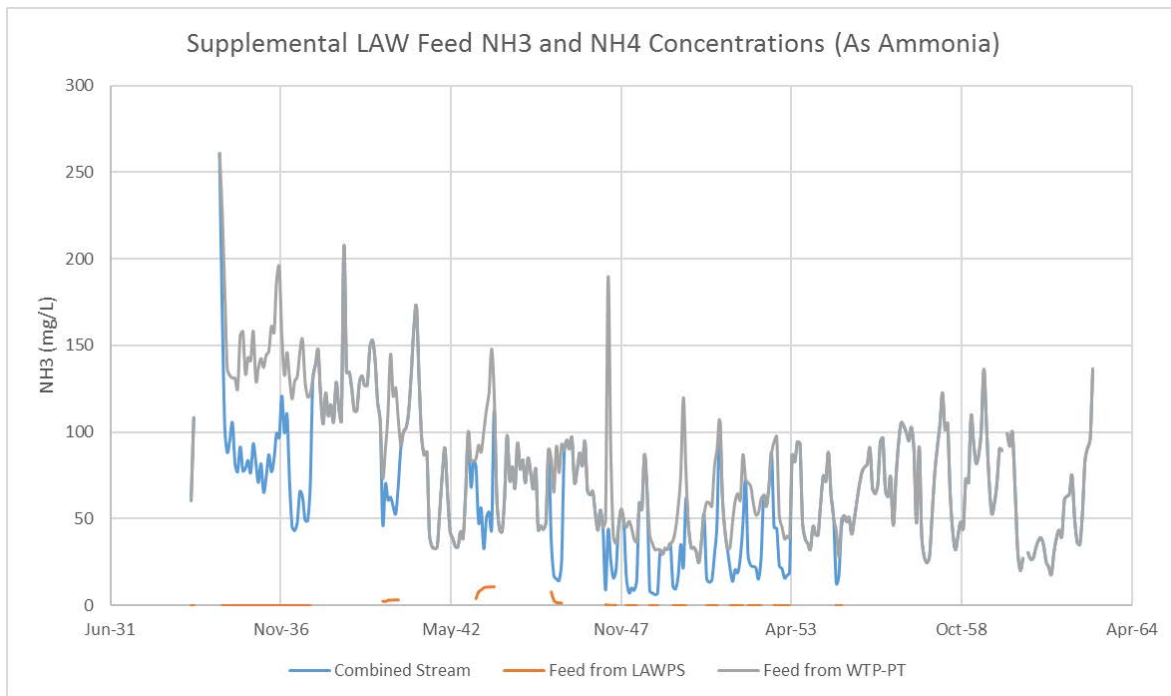


Figure M-5. Ammonia Concentration

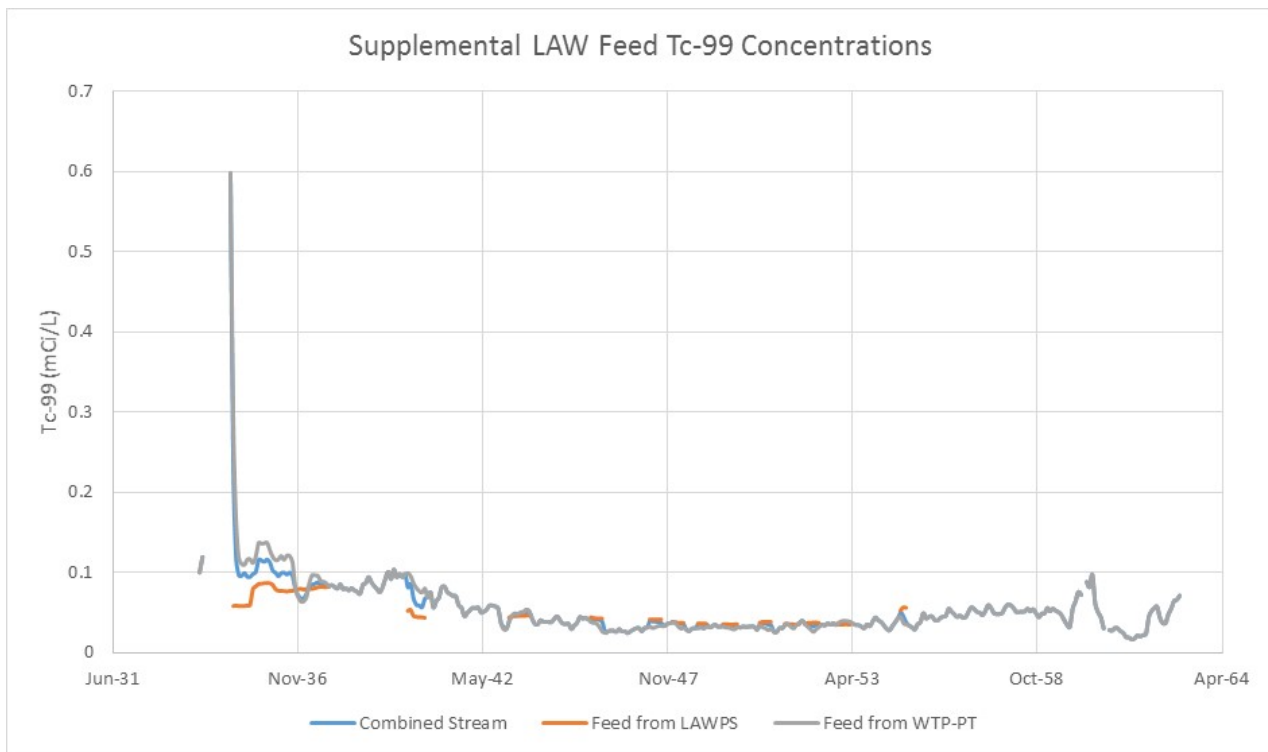


Figure M-6. Tc-99 Concentrations

In addition, as a result of the unconstrained model and the desire to achieve full capacity through the HLW vitrification facility, the Supplemental LAW will also need to accommodate extremes in feed volume, as shown in Figure M-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 Supplemental LAW.

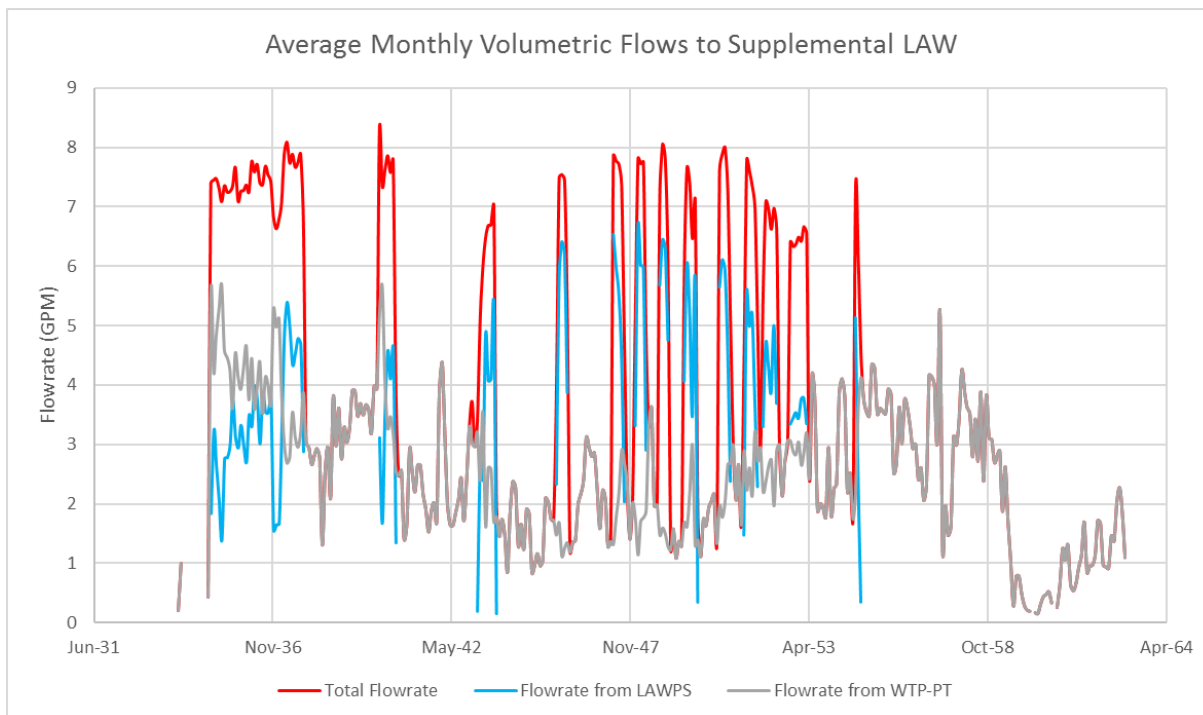


Figure M-7. Supplemental LAW Feed Volumes

M.2.3.3 Integrated Flowsheet

The One System Integrated Flowsheet was utilized as the source for the Supplemental LAW 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 Supplemental LAW 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 document¹⁰ 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
- Supplemental LAW 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 (¹²⁹I, ⁹⁹Tc, S, Cl, F, e.g.) in the feed to Supplemental LAW¹¹. 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 Supplemental LAW 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 Supplemental LAW 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 Supplemental LAW feeds to prevent the most extreme conditions noted in the current feed vector. Thus, a proposed flowsheet should not be automatically eliminated from consideration if a small set of conditions noted in the current vector are outside the ranges possible with the flowsheet.

M.3 FLYWHEELS AND IMPACT ON SLAW

M.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.

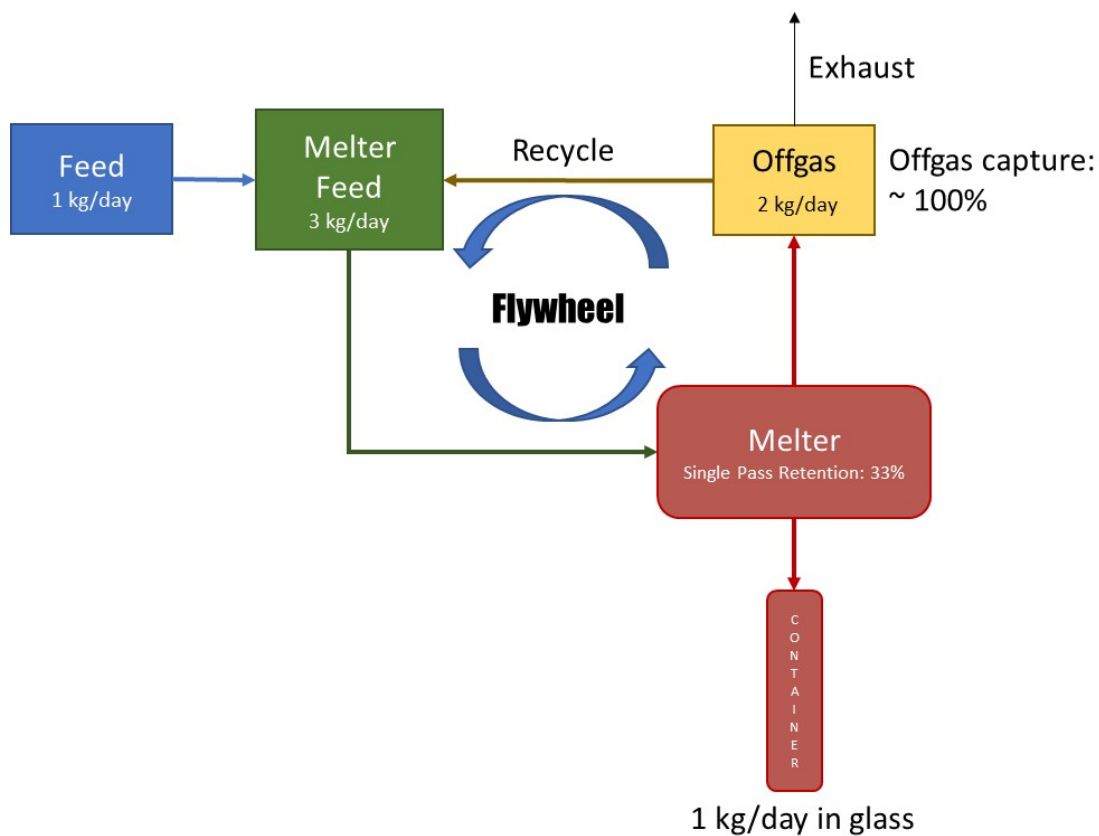


Figure M-8. Simplified Flywheel.

The flywheel in the LAW system after startup of SLAW is more complicated, as is shown in Figure M-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.

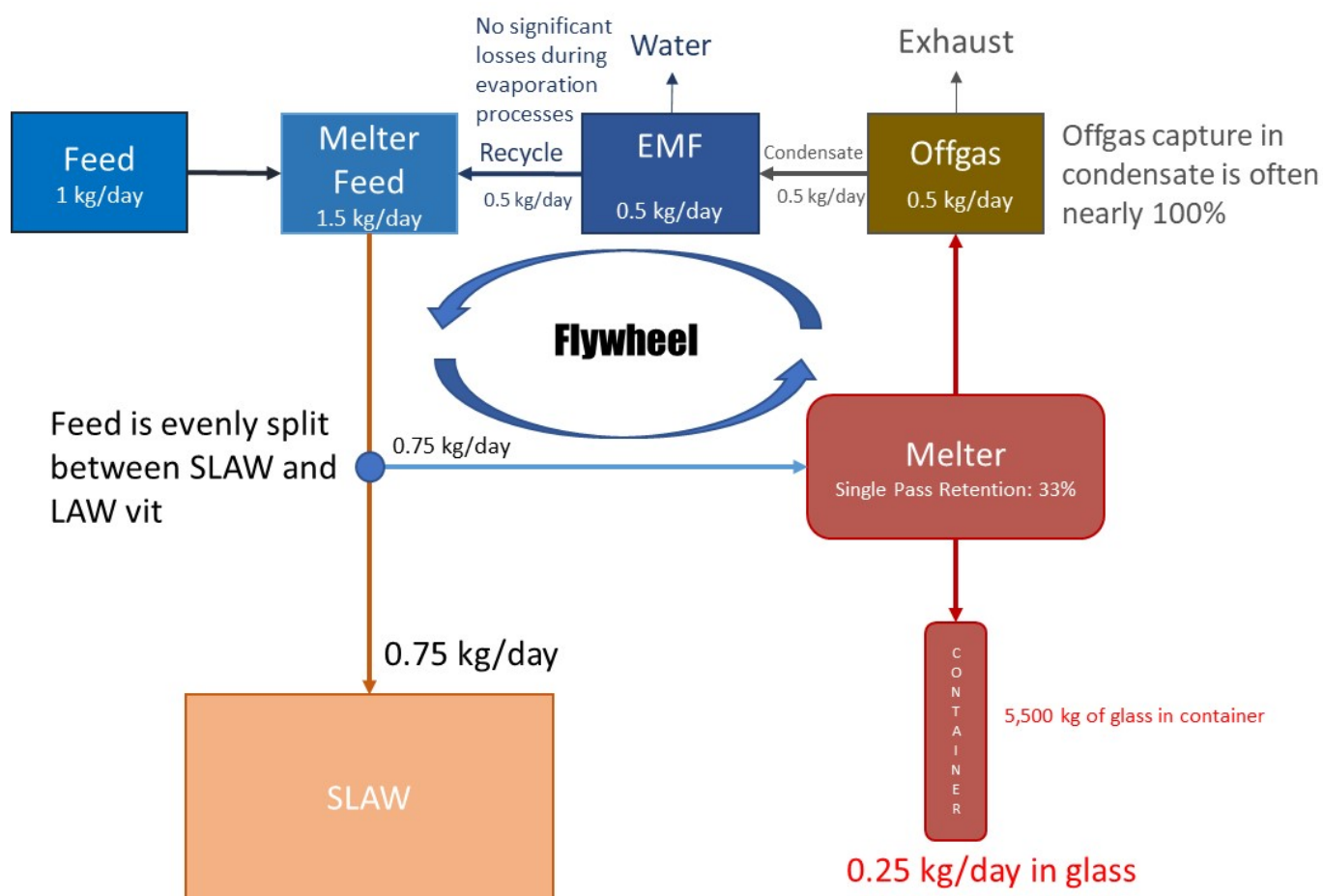


Figure M-9. LAW Flywheel

M.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 Ly, 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 waste form 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.

M.4 CONCLUSIONS

The feed vector provided by WRPS is the best information available and has been used to perform the assessment of proposed flowsheets for supplemental LAW disposition. The capacity of the Supplemental LAW facility should be based on the flowrates to Supplemental LAW 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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ATTACHMENT 1. TEAM BIOS

To be added to final report.

ATTACHMENT 2. NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 2017, SECTION 3134, "ANALYSIS OF APPROACHES FOR SUPPLEMENTAL TREATMENT OF LOW-ACTIVITY WASTE AT HANFORD NUCLEAR RESERVATION"

To be added to final report.

ATTACHMENT 3. PROGRAM PLAN FOR ANALYSIS OF APPROACHES TO SUPPLEMENTAL TREATMENT OF LOW-ACTIVITY WASTE AT THE HANFORD NUCLEAR RESERVATION

To be added to final report.