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

The following attached documents have been developed by the FFRDC Team and represent "working draft" information 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It is important for readers to understand that much of what is presented in these working draft documents has not been peer reviewed or technically edited and is not intended to imply any final conclusions or represent a complete analysis.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 fall of 2018 and spring 2019. Until a final report is issued, all information presented is considered Pre-Decisional DRAFT.

The intent of sharing the working draft documents is to stimulate dialog with the NAS Committee members and to ultimately obtain constructive feedback, comments, and technical ideas to improve on these draft documents and technical concepts as they mature into the ultimate final report(s).

Bill Bates

FFRDC Team Lead

Savannah River National Laboratory™

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

July 2018

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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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ACKNOWLEDGEMENTS

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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
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
WTP	Waste Treatment and Immobilization Plant

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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 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.

NDAA17 also 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.

This FFRDC core team was constituted through the Environmental Management National Laboratory Network (EMNLN), which recommended experts from the national laboratories who were accomplished in disciplines pertinent to key aspects of the analysis.

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 of those approaches.

This main body of this report provides an overview of the base ad variant cases and the analysis of each one. Details are included in the appendices.

This report provides results of the analysis of each option based on expert analysis of a broad set criteria. Non-technical parameters such as acceptance to stakeholders and political considerations were excluded from this analysis. The information in this report does not constitute formal design quality that would be required for conceptual design for any of the alternatives in the event that they are selected for implementation.

1.0 PARAMETERS OF THE ANALYSIS

1.1 STRATEGY

As summarized in Table 1-2, the "Best Practices for the Analysis of Alternatives" established by the United States Government Accountability Office (GAO)[1] 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.[2] 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.[3]

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 FFRDE 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.[4] 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.[5]

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 of those methods. The analysis included the following major elements:

- Development of pre-conceptual flow sheets

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[1] 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.

[2] "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.

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

[4] "EM National Laboratory Network Charter." May 2017.

[5] "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 variants, options, and opportunities
- Development of criteria for analysis and comparison of options
- Review of regulatory requirements for processing, transport, and disposal
- 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 base cases as well as 9 variants identified by the team and then performed comparisons among the options.

Section 7.0, "Analysis Summary," provides the grading criteria and comparison of the options.

Table 1-1 Application of GAO Best Practices for the Analysis of Alternatives

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."
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 AOA team completed the AOA over a time spam of approximately two years.
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.
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 analysis.
	Process Included in the General Principle Category (continued)	

7	The team documents and justifies all assumptions and constraints used in the analysis	Each alternative package developed incudes a section documenting all assumptions and constraints. These assumptions and constraints are identified in Table XX "Supplemental LAW Options and Areas of Considerations."
8	The team conducts the analysis without a predetermined solution	The analysis includes 12 cases and no predetermined solution.
	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 no predetermined solution.
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 2-melter vitrification.
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 cost estimates for each alternative, using existing data and making appropriate adjustments to levelize all estimates at with consistent dollars that were used for comparison purposes among the alternatives, including retirement of the facilities.
	Process Included in the Identifying Alternatives Category (continued)	
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 -50% to + 100%.
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 subjective.
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.
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.
	Process Included in the Selecting a Preferred Alternative	
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 FFRDE team does not provide a recommended or preferred alternative.
	Process Included in the Selecting a Preferred Alternative (Continued)	
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.

1.2 SCOPE

The Section 3134 of NDAA2017 specifies: "Not later than 60 days after the date of the enactment of this Act, the Secretary of Energy shall enter into an arrangement with a federally funded research and development center to conduct an **analysis of approaches for treating the portion of low-activity waste** at the Hanford Nuclear Reservation, Richland, Washington, **that, as of such date of enactment, is intended for supplemental treatment."**

The only documentation specifying the feed stream intended to be processed through the Supplemental LAW 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 issued[6]; Revision 2 was still in draft. Revision 2 was issued in September, 2017 based on processing assumptions in System Plan 8 and utilized updated glass modeling to reduce the size of the Supplemental LAW facility required. The models utilized during Revision 2 also allowed extraction of a monthly feed vector to Supplemental LAW while Revision 1 could only be utilized to provide an overall mission average. Older documents contain feed vectors for LAW[7][8], 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 is assumed to be the Supplemental LAW feed vector from Revision 2 of the Integrated Flowsheet[9]. The initial evaluation of each flowsheet will utilize the Supplemental LAW feed vector with no modifications, and additional pre-treatment will be evaluated as needed. PT will be 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 previously[10] as well as the impacts of a 20% variation for selected components on the baseline process[11]. The evaluation of uncertainty determined that 20% is not a bounding

[6]S.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.

[7] D.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.

[8] J.R. Baker, "Supplemental Treatment Project Immobilization System Feed Composition - Revision 0," AEM Consulting, Richland, Washington, SVF-2007, 2010.

[9] 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.

[10] 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.

[11] 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.

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 at the Savannah River Site indicates that compositions of the tanks can be different than expected and that operational issues can lead to frequent departures from the planned retrieval sequence[12].

Third, the TOPSim model used to generate the feed vector has many simplifications[13]. 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 affect the recycle streams from the HLW and LAW melter offgas systems and could lead to non-conservative assumptions of semi-volatile species (^{129}I, ^{99}Tc, S, Cl, F, e.g.) in the feed to Supplemental LAW[14]. The single parameter split factors do not account for any process variation from changing feed compositions, but it is difficult 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 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 TOPSim[15]. 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.

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[12] 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.
[13] 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.
[14] 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.
[15] Pierson, K. L. "Evaluation of the HTWOS Integrated Solubility Model Predictions." RPP-RPT-53089. 2012. Washington River Protection Solutions. Richland, Washington.

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 that 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)[16]. It is noted that acceleration of the mission is not simply a matter of building a bigger 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. 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 treatment options to be considered 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) is in progress, but not finalized. Any immobilized waste sent to IDF would need to meet these new requirements, but a lack of a final product leads to uncertainty in the evaluation for each waste form. Major changes are not expected from the drafts provided; therefore, the evaluation is proceeding at risk using the values in the draft PA.

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[16] 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.

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 8[17]. 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.

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 closed" by isolating these tanks from other tanks by cutting and sealing transfer lines in and out of the tanks and the infrastructure that supported transfers was not maintained. Retrieval of waste from "C" farm has been completed, but challenges were identified, e.g. tank vapors, that slowed work. Resolution of these issues as well as the completion of the required upgrades is assumed in System Plan 8. In addition, System Plan 8 assumes retrieval and transfer efficiencies/improvements that have not yet been demonstrated by tank farm operations. The number of transfers needed to be performed in a year will need to increase by orders of magnitude to support WTP operation; the ability to accelerate processing to the levels assumed in System Plan 8 is not certain.[18]

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 deployed at 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.

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

[18] Kosson, D. S.; D. R. Gallay, I. L. Pegg, R. G. Wymer. "External Technical Review of System Planning

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. However, 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. 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 F, "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 reflect significant increases in unit operations or complexity, or reductions in same. This limited number of individual estimates, but does not reflect the range expected for the various technologies. 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 Rough Order of Magnitude comparison.

The project team 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.

See Appendix G for full discussion.

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.[19]

The waste has been stored in 177 underground, carbon steel storage tanks. Many of these tanks are known to have developed leaks[20]; 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.[21]

The Hanford Waste Treatment and Immobilization Plant (WTP) is a complex of facilities[22] designed to receive waste from the storage tanks and perform all pretreatment processes to prepare the waste for immobilization

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[19] 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.
[20] 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.
[21] Smith, R.D. "Tank Farms Documented Safety Analysis." RPP-13033. Revision 7-G. 2017. Washington River Protection Solutions. Richland, Washington.
[22] 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.[23] A simplified diagram showing the tank farm, WTP, and other facilities required is shown in Figure 2.1.

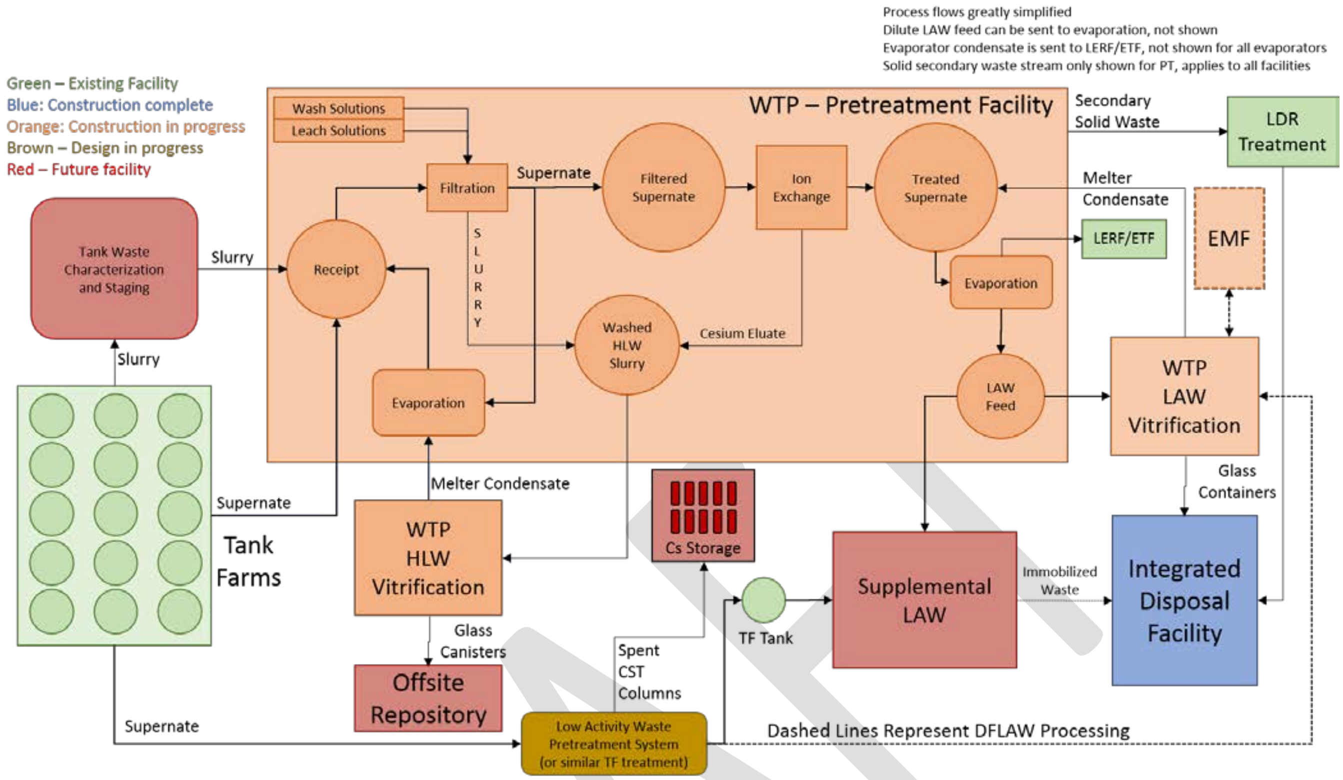

Figure 2-1 Simplified Flow Sheet for Immobilization of Hanford Waste during Full WTP Operation

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

[23] "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.[24]

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.[25] 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.

[24] 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.
[25] Cree, L.H. "Re: Some Pending Requests for Help. " Email from Laura Cree to Michael E Stone. 2017. Accessed on: Available at

2.2 SUMMARY OF OTHER OPTIONS CONSIDERED DURING THIS EVALUATION

As stated above, a decision on the technology for Supplemental LAW has not been made, but vitrification using melters to generated containers of immobilized LAW waste with disposal at the IDF is the assumed baseline technology.

Bulk vitrification has been evaluated in the past for LAW immobilization and is an option evaluated during this review.

Grout is also mentioned as an option in the Integrated Flowsheet and will be considered as an alternate to vitrification during this review. Steam Reforming also is considered as a treatment option.
The list of options considered and elected for evaluation are found in section 7.0. Offsite disposal includes sending the treated LAW supernate to a commercial vendor for immobilization and shipment to a commercial disposal facility or simply sending the immobilized product from an onsite immobilization facility to the commercial site. It is noted that treating individual tanks could lead to feed compositions to Supplemental LAW not bounded by feed vector from the Integrated Flowsheet, but it should be expected that tanks that would challenge the treatment technology would not be selected for individual treatment.

Options not selected for additional consideration during this review include:

- Immobilization of LAW into a hydroceramics[26]
- Vitrification into a non-borosilicate glass[27]
- Disposal of immobilized LAW at other DOE sites.]

2.3 FEED VECTOR

The Supplemental LAW feed vector[28] calculated for the One System River Protection Project Integrated Flowsheet[29] 6 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.

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[26] Bao, Y.; M.W. Grutzeck and C.M. Jantzen. "Preparation and Properties of Hydroceramic Waste Forms Made with Simulated Hanford Low Activity Waste." Journal of the American Ceramic Society. Volume 88, Issue12. December 2005. Pages 3287-3302.

[27] Kim, D.S.; W.C. Buchmiller, M.J. Schweiger, J.D. Vienna, D.E. Day, C.W. Kim, D. Zhu, T.E. Day, T. Neidt, D.K. Peeler, T.B. Edwards, I.A. Reamer, and R.J. Workman. "Iron Phosphate Glass as an Alternative Waste-Form for Hanford LAW." PNNL-14251. 2003. Pacific Northwest National Laboratory. Richland, Washington.

[28] Cree, L.H. "Re: Some Pending Requests for Help. " Email from Laura Cree to Michael E Stone. 2017. Accessed on: Available at

[29] 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.

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 that the values shown.

The varied methods used during the nuclear material separations processing at Hanford resulted in waste that varies significantly in composition. Typically, these varying waste types are segregated across the tank farms (although some incidental blending has occurred and will occur during retrieval) which can result in large swings in feed composition to the 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.

2.4 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 document[30] 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 (^{129}I,

[30] 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.

^{99}Tc, S, Cl, F, e.g.) in the feed to Supplemental LAW.[31] 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.

2.5 CONCLUSIONS

The feed vector provided by WRPS 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.

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

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."[32] 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. There are several areas of risk assessment that are relevant to the NDAA study, including:

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."[33] 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."[34]
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.[35] 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.[36]

3.3 APPLICATION OF RISK ASSESSMENT TECHNIQUES

The FFRDC team (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 support the evaluation of the alternatives, as well as estimating the total cost of each alternative. In addition, for the final disposal of the immobilized LAW, the team assessed the potential for compliance with disposal site

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[32] "Risk Assessment." *English – Oxford Living Dictionaries*. Oxford University Press. Undated. https://en.oxforddictionaries.com/definition/risk_assessment. Web. 17 January 2018.

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

[34] "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.

[35] "About Risk Assessment." Risk Assessment. United States Environmental Protection Agency. https://www.epa.gov/risk/about-risk-assessment#whatisrisk. Web. 17 January 2018.

[36] "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.

performance objectives. Specific approaches applied to each of these risk assessment activities are described below.

3.3.1 Alternatives Risk Assessment

For each technology and its corresponding flowsheet, once narrowed to a finite list of options/alternatives 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. “Risks and Opportunities” represents a specific LOI, that is defined to address several key risks including:

- Project risks associated with engineering, design, construction, and commissioning of the defined alternative
- Operational execution risks representing the life of operations of the facilities once constructed
- Technology maturation (aka technology readiness level [TRL]) risks associated with advancing each alternative to operational status of maturity (e.g., TRL 8-9).

A set of semi-quantitative metrics or definitions were also established to aid the Team in assessing each alternative against all LOI criteria. For the Risk LOIs, the Team chose a high, med, and low risk approach, where each alternative will be compared against the other alternatives in each of the three risk areas above – project, operational, and technology maturation. An expert elicitation approach was used to provide relative, semi-quantitative evaluation of risks, with the Team members serving as the evaluation experts.

While this LOI focuses principally on explicit consideration of future project risks associated with delivering and operating the alternative processes, many of the other LOI criteria and their metrics also have implicit risk considerations. For example, the *TRL and Complexity* LOI includes consideration of challenges with major equipment replacement, and difficulty handing off-specification waste products as inputs. The *Robust Operational Flexibility* LOI includes consideration of compatibility of each alternative with challenging constituents and all feed streams. In addition, Regulatory, Safety, Cost, and Schedule LOIs will consider uncertainty and risks, and therefore assumptions and considerations in the evaluation of each alternative are documented, highlighting potential risks identified for each alternative specific to each criteria.

3.3.2 Disposal Environmental Risk Assessment

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, a final approved WAC does not exist. In addition, the available DRAFT WAC, for LAW, is explicit to glass. Therefore, to evaluate and compare the Study alternative waste forms on an “apples to apples” basis, an IDF disposal assessment will be performed by the Team to assess the potential performance of each alternative waste form in an IDF environment. This approach is very similar to that conducted in 2003 for the initial supplemental treatment alternatives assessment. [37]

The approach proposed for this assessment (aka Risk Assessment, or Mini-PA) 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 Assessment, 2014 EIS, and 2017 IDF Performance

[37] Mann et al. Risk Assessment

Assessment[38] are 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., Tc^{99}, I^{129}). 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 are 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 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).

[38] 2003 Risk Assessment, 2014 EIS, and 2017 IDF Performance Assessment

4.0 ASSESSMENT AREA SUMMARIES

4.1 PRETREATMENT

TBD

See full discussion in Appendix A.

4.2 VITRIFICATION

TBD

See full discussion in Appendix B.

4.3 STEAM REFORMING

TBD

See full discussion in Appendix C.

4.4 GROUT

TBD

See full discussion in Appendix D.

4.5 OTHER APPROACHES

TBD

See full discussion in Appendix E.

5.0 SUMMARY OF DISPOSAL SITE CONSIDERATIONS

TBD

See full discussion in Appendix H.

6.0 SUMMARY OF TRANSPORATION CONSIDERATIONS

TBD

See full discussion in Appendix I

7.0 COMPARATIVE ANALYSIS OF APPROACHES SUMMARY

TBD.

See full discussion in Appendix F.

APPENDIX A. EXPANDED DISCUSSION – PRETREATMENT

A.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 place of glass. These pretreatment processes would 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.

A.2 REQUIREMENTS

A.2.1 Strontium

The removal requirements for Sr, if determined to be needed, are based on providing a significant degree of waste reclassification to justify the additional processing cost. As shown in Table A.1, with no Sr removal, grouting the base-line feed vector will result in the waste being classified as Class C for 33 of the 441 months with the balance being classified as Class B. The TRU content of the Feed Vector for the 33 of the month is the driving factor to Class C waste. 90% to 95% Sr removal only reduces the amount of Class B waste by 17-23%, whereas 99% Sr removal shifts 99.5% of the Class B waste to Class A. Table A.2 provides a similar analysis for glass or Steam Reformed waste packages.

Table A.1. Impact of Sr removal on Waste Classification for Grout

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

Table A.2. Impact of Sr removal on Waste Classification for Glass or Steam Reformed Waste

Glass or Steam Reformed (2600 kg/m3, all nuclides and 1.0 multiplier)					
% Sr-90 removal	GTCC (months	Class C (months)	Class B (months)	Class A (months)	Notes
None	0	42	399	0	TRU's 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 is predicted by the TOPSim model is based on the Integrated Solubility Model (ISM). ISM was shown to poorly predict soluble 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 would still require some treatment to allow the waste to meet Class A requirements.

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

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

A.2.2 Technetium

The basis for the Tc removal is the 2017 Integrated Disposal Facility (IDF) Performance Assessment (PA). The underlying assumptions are that:

- Liquid Secondary Waste (LSW) grout is conservative relative to performance of ILAW grout
- LSW performance extrapolation linear to much higher Tc inventories
- Fraction of Tc inventory for SLAW is 50%.

Based on these assumptions and a maximum ground water limit of 900 pCi/l to meet regulatory requirement an overall Tc removal of ~92.2% would be required for a grout waste form. To limit the ground water 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 may be significantly better than the LSW grout; therefore, the required pretreatment evaluated is assumed to be conservative.

A.2.3 Iodine

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

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

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

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

A.2.4 LDR Organics / Metals

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. Further information is needed on the types and amounts of organic species to determine whether treatment for organics is required. 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 assumed to be 50 to 90%, but the final determination of the required treatment cannot be performed until the organics in the waste feeds are better characterized..

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 noted that RCRA metal pretreatment is not considered as likely to be required, but the final determination of the required treatment needed cannot be performed until the waste feeds are better characterized.

A.3 SELECTED PRETREATMENT TECHNOLOGIES

A.3.1 Strontium

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

A.3.1.1 Solvent Extraction

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

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

A.3.1.2 Ion Exchange

Sylvester et al, (19xx) 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, $Na_2Ti_2O_3SiO_4 \cdot 2H_2O$ (NaTS), was the best material in NCAW with a *K*d of 2.7 x 10^5 mL/g at a volume-to-mass ratio of 200:1. In the 101SY-Cs5 simulant, strontium extraction was more difficult due to the presence of complexants and consequently *K*ds were greatly reduced. Sodium nonatitanate, NaTi, performed best in the presence of these complexants and gave a *K*d of 295 mL/g, though none of the materials performed particularly well. Both the sodium titanate and the sodium titanosilicate performed better than IONSIV IE-911, a commercially available ion exchanger, in the NCAW simulant, and consequently could be used for the removal of ^{90}Sr from highly alkaline tank wastes.”

Monosodium Titanate
Wilmarth et al, (2011) conducted a review of pretreatment technologies that addressed both Se 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 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 was evaluated and determined to be at TRL 6. Laboratory scale tests with real wastes and full scale tests with a range of simulants using prototypical equipment have been completed.

Complexed Sr removal

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

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

A.3.2 Technetium

A.3.2.1 Solvent Extraction

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

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

A.3.2.2 Ion Exchange

The review of pretreatment technologies conducted by Wilmarth et al., (2011) that addressed both Se 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 A.3 from that report lists batch-distribution values for sorption of Tc from a simulated high-organic tank waste for the most promising material examined at that time. It should be noted that SuperLig® 639 resin was not being manufactured at the time the TWRS program conducted these tests.

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

Table A.3. Batch distribution ratios (Kd) for sorption of Tc from a Hanford Tank Waste Simulant containing organic complexants (Wilmarth et al., 2011)

Ion exchanger	Description	*Kd*, mL/g[a]
Purolite A-520E	Macroporous anion exchanger with triethylamine groups	1,300
Ionac SR-6	Macroporous anion exchanger with tributylamine groups	1,170
Reillex HPQ	Copolymer of 1-methyl-4-vinylpyridine and divinylbenzene	670
n-butyl-Reillex HP	*n*-butyl derivative of poly-4-vinylpyridine/divinylbenzene (Reillex™ HP)	1,405
iso-butyl-Reillex HP	iso-butyl derivative of Reillex™ HP	810
n-hexyl-Reillex HP	*n*-hexyl derivative of Reillex™ HP	1,405
n-octyl-HP	*n*-octyl derivative of Reillex™ HP	780
TEVA·Spec	Methyltricaprylammonium chloride (Aliquat™ 336) sorbed onto an acrylic ester nonionic polymer	1,280
Alliquat 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 a dual-column configuration, each containing a 5-mL resin bed for four Hanford tank supernates. Two tank-waste supernates exhibited a high fraction of nonextractable technetium (nonpertechnetate): AN-102/C-104 was 50% nonpertechnetate, and AP-104 was 69% nonpertechnetate. The pertechnetate removal for all tested supernates, showed an average of 99% removal for supernates that were essentially all pertechnetate and .86% removal for supernates that contained a high fraction of nonpertechnetate. The column elution was conducted using 65°C water and resulted in 99% elution on average within 16 bed volumes of eluant.

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

Gasper et al also state:

> The valence state of the soluble technetium in the Hanford Site tank wastes is predominantly +7, with technetium present as the pertechnetate (TcO^-_4) anion. SuperLig 639 resin is capable of

only removing technetium present as the pertechnetate anion. Batch contact and laboratory-scale ion exchange column tests have indicated that 1 to 5 percent of the technetium present in samples of non-complexed tank wastes is not present as the pertechnetate anion and cannot be extracted using SuperLig 639 resin (WSRC-MS-2001-00573)

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

A.3.3 Iodine

Iodine removal from tank waste supernates has not been evaluated to the extent of other radionuclides. Selected laboratory studies were found using silver 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%.

A.3.4 LDR

A.3.4.1 LDR Organics

There are several organic management methods that could be applied. These include Chemical Oxidation (CHOXD) and Recovery of Organics (RORGS). CHOXD could be accomplished with the addition of permanganate or peroxides. RORGS includes the use of carbon adsorption, liquid / liquid extraction and physical phase separation or centrifugation. For this application, the addition of permanganate is proposed. 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.3.4.2 LDR Metals

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

A.4 APPROACH TO PRETREATMENT

The conceptual flow sheet for pretreatment is shown in Figure A.1. It consists of 4 primary treatment blocks, some or all of which can be bypassed based on pretreatment needs for specific batches of feed.

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

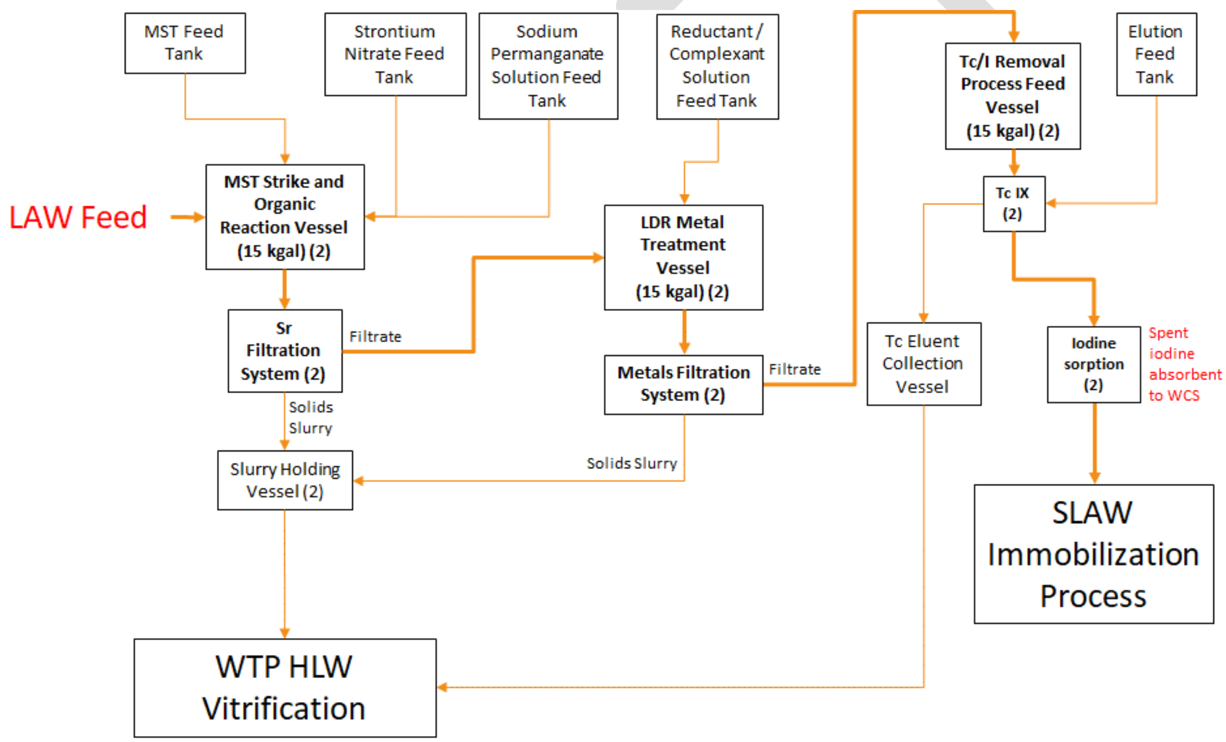

Figure A.1. Supplemental LAW Pretreatment Concept

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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).[39] 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.[40] 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 melter offgas treatment system will condense the water and volatile components as well as remove entrained particulate from the offgas.[41] 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.[42] These effluents will be evaporated and the overheads are transferred to the Liquid Effluent Receipt Facility/Effluent Treatment Facility (LERF/ETF) for further treatment. The concentrate will be and 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 lessons learned 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 handing, decontamination, and temporary lag storage facility. Each of these unit operations is outlined in the figure below and described in the following subsections.

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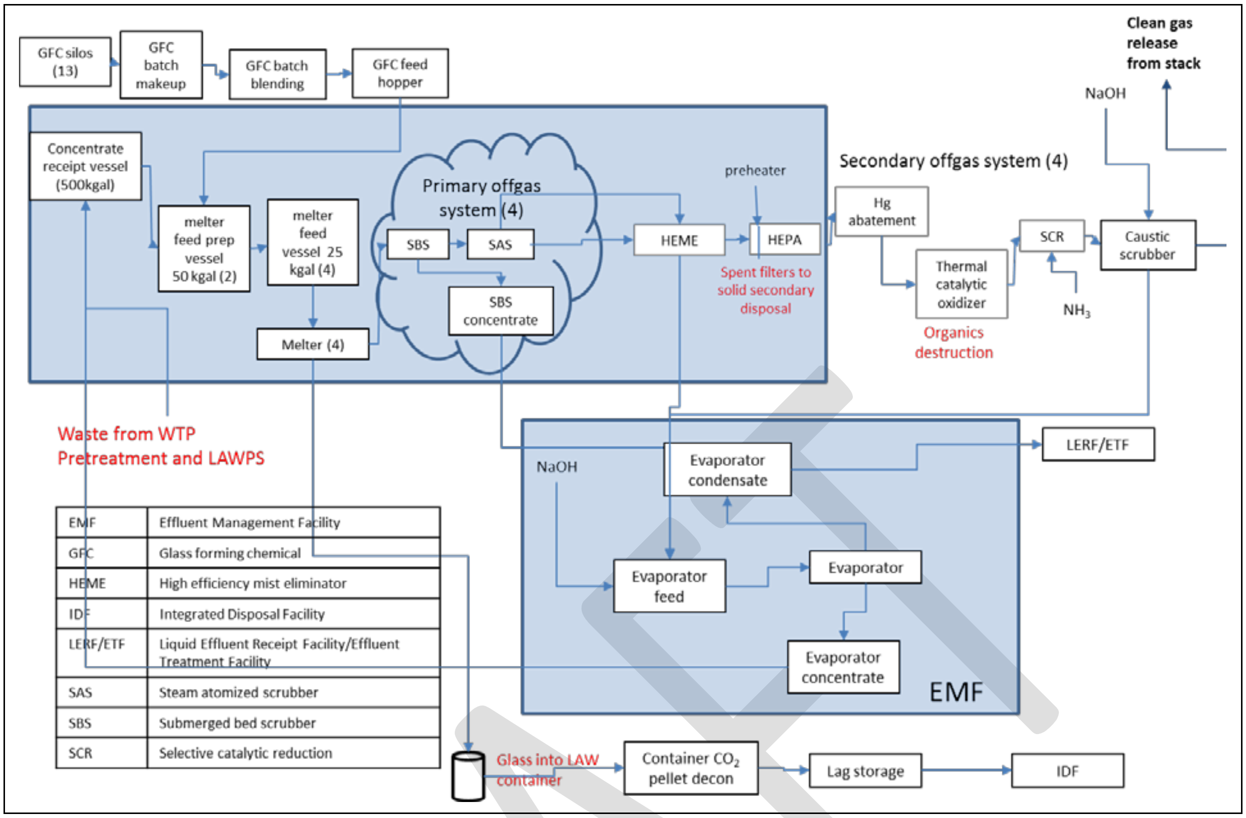
[39] "LAW Melter Feed Process (LFP) and Concentrate Receipt Process (LCP) System Design Description," Bechtel National Incorporated, River Protection Project, Waste Treatment Plant, Richland, Washington, 2017.

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

[41] "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.

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



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 for 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[43,44] to determine the GFC and sucrose additions required for formulation of a compliant glass.[45] This differs somewhat from the WTP LAW facility, where sampling for compliance will occur in the CRV, though the MFPV will still be sampled.[46] This sample is considered a process hold point to demonstrate waste compliance.[47] 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 a preparation system is assumed to be of the same design and capability as those of the WTP Balance of Facilities (BOF) glass former handling facility,[48] but with its scale doubled to support

[43] 24590-LAW-RPT-RT-04-0003, Rev 1, Preliminary ILAW Formulation Algorithm Description
[44] 24590-101-TSA-W000-0009-72-00012, Letter Report – Proposed Approach for Development of LAW Glass Formulation Correlation
[45] 24590-WTP-PL-RT-03-001, ILAW Product Compliance Plan
[46] "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.
[47] "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.
[48] 24590-LAW-3ZD-LFP-00001, LAW Melter Feed Process (LFP) and Concentrate Receipt Process (LCP) System Design Description

the operation of four melters. The GFCs, their mineral sources,[49] and acceptable levels of impurities[50] 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 GFCsThe blended GFCs will be wetted to prevent dusting[51] and fed to the MFPV. Dilution water massis added to the feed if needed to meet melter feed rheological requirements,[52] 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.[53]

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.[54] 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.[46] The glass must meet melter compatibility requirements including viscosity, electrical conductivity, and liquidus temperature.[55] These properties are controlled via glass formulation as dictated by the glass property models.[43,44]

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

[49] R.F. Schumacher, "Characterization of HLW and Law Glass Formers," Westinghouse Savannah River Company, Aiken, SC, WSRC-TR-2002-00282, Rev. 1, 2003.
[50] SCT-M0SRLE60-00-175-01, Final Report - Characterization of HLW and LAW Glass Formers
[51] CCN 077705, Evaluation of Wetting Agents for Glass Former Dusting Control (RTC 170)
[52] 24590-WTP-RPT-PO-03-007, LAW Melter Feed Rheology Assessment
[53] 24590-WTP-RPT-PT-02-005, Rev 8, Flowsheet Bases, Assumptions, and Requirements
[54] 24590-101-TSA-W000-0010-409-359, LAW Melter System Description
[55] 24590-LAW-3PS-AE00-T0001, Engineering Specification for Low Activity Waste Melters

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 crystallive formations to form that would require replacement of the melter.

The resulting glass exits the melter via one of two 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.[46] Bubbler replacement is expected to be the most frequent maintenance requirement,[46] with each bubbler having an estimated life span of 26 weeks.[56,57]

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.[46] 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.[46]

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 condensation in the system 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 concentrate 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 support 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.[58] 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 encapsulation as Secondary Solid Waste prior to disposal at the IDF.[59] The resulting offgas will exit the radioactive containment area and will be treated to remove mercury, acid gas, and halides using 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

[56] 24590-101-TSA-W000-0009-23-10, Rev 00C, Report – RPP Pilot Melter Bubbler Life Extension Test Results Report
[57] CCN 103214, Update to the LAW Reliability, Availability, and Maintainability (RAM) Data for the LCP, LFP, LMP, GFR, LOP, and LVP Systems
[58] 24590-LAW-3YD-LOP-00001, Rev 3
[59] "River Protection Project System Plan," ORP-11242, Revision 8, DOE Office of River Protection, Richland, Washington, 2017.

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. 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 LAWPS 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. It is assumed that LERF/ETF has sufficient capability to process condensate from the SLAW EMF.

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.[46] For comparison, the SRS Defense Waste Processing Facility (DWPF) returns 5 gallons of liquid to the tank farm for each gallon of sludge vitrified.[60] Therefore, there is a risk that the current ILAW flowsheet underestimates the volume of liquid secondary waste that will be produced.

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.[46] 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.[61,62,63,64]

The vitrified waste is poured into the containers, which hold ~6 metric tons (~2,000 gal) of vitrified waste.[46] The containers are cooled, inspected for fill height (if fill height is not ≥ 90%, inert fill is added), and sealed. The sealed containers are decontaminated by CO_2 pellet blasting to meet requirements for minimal removable contamination. This system is assumed to be of the same design as that for WTP LAW.[46,65] The gas and particulate stream is drawn through HEPA filters, and then exhausts to the building ventilation system. Spent HEPA filters will be transferred to the Central Waste Complex for encapsulation as Secondary Solid Waste prior to disposal at the IDF.[66] Finished containers are stored until transfer to the IDF.

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[60] "DWPF Recycle Evaporator Flowsheet Evaluation (U)," WSRC-TR-2005-00226, Revision 1, Savannah River National Laboratory, Aiken, South Carolina, 2005.
[61] 24590-LAW-3ZD-LRH-00001, Rev 0, LAW Container Receipt Handling (LRH) System Design Description
[62] 24590-LAW-3ZD-LPH-00001, Rev 0, LAW Container Pour Handling (LPH) System Design Description
[63] 24590-LAW-3ZD-LFH-00001, Rev 0, LAW Container Finishing Handling (LFH) System Design Description
[64] 24590-LAW-3ZD-LEH-00001, Rev 0, LAW Container Export Handling (LEH) System Design Description
[65] 24590-LAW-M5-V17T-00013, Process Flow Diagram LAW Vitrification Container Decontamination (System CDG)
[66] "River Protection Project System Plan," ORP-11242, Revision 8, DOE Office of River Protection, Richland, Washington, 2017.

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 far 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 Next Generation Melters/Carbon Steel Containers

The first alternative flowsheet will maintain the waste feed preparation systems and methodology of the baseline flowsheet. The four melters in the baseline flowsheet will be replaced by two, larger, next generation melters (NGM). The melters will have a larger surface area and thicker refractories than the WTP LAW melters. The melters will operate at a higher temperature (within the design range of the WTP LAW melters), leveraging the increase in refractory to maintain melter life at the high temperature.

Each melter will have a dedicated primary offgas train and share a secondary offgas train. A redundant primary and secondary offgas train will be available to maintain production during offgas train maintenance. The melters will utilize both of the pour spouts associated with the melters (WTP LAW melters have two pour spouts but can only pour from one at a time). It is expected that the two NGMs can meet the production rate of the four WTP LAW melters.

Vitrified waste will be poured into carbon steel containers that meet the performance requirements of the stainless steel containers in the baseline flowsheet.

B.2.2.3 Bulk Vitrification

For Bulk Vitrification, the SLAW facility will receive treated supernate from the WTP PT and LAWPS.[39] Pre-blended GFCs and sugar or 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.[67] 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.

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

B.3 ASSUMPTIONS

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

- Tank waste retrieval and pretreatment via WTP PT and LAWPS are fast enough to maintain continuous feed to 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 flowsheet 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
- 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
- The current ILAW flowsheet underestimates the volume of liquid secondary waste that will be produced

Risks associated with the alternative flowsheet 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

APPENDIX C. EXPANDED DISCUSSION – STEAM REFORMING

INTRODUCTION

Fluidized bed steam reforming (FBSR) has been researched, developed, and used commercially for over two decades for processing low level radioactive wastes. The commercial Erwin Resin*Solutions* Facility (formerly Studsvik Processing Facility) in Erwin, TN began operation in the late 1990's 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) were 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 design and operating conditions of the FBSR process. If the goal of the FBSR process is to primarily evaporate water, destroy nitrates, or destroy organics, without the need to produce a durable, solid waste form to contain the solid residue, then the FBSR may be operated to produce a solid product that is not durable, leach resistant solid waste forms. If the goal of the FBSR process is to accomplish all of the above and also convert the solid residue into a durable, leach-resistant waste form, then the FBSR process can be designed and operated to accomplish all those goals.

Durable, Leach-Resistant Mineralized Na-Al-Si Waste Form

Selected FBSR research and development programs for treating various liquid radioactive wastes performed between 2001 and 2011 are summarized in Table C-1 (from the 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 2015a]). This table does not include all FBSR demonstrations between those years, but it focuses on those programs intended to produce a durable, leach-resistant mineralized Na-Al-Si waste form, designed to be "as good as glass," from Hanford LAW. Studsvik, Inc. has also continued to develop and demonstrate steam reforming for various world-wide customers including ORANO (formerly AREVA). Various additional references for this table and for other tests 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 the FBSR concept that would be Hanford SLAW.

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 or Savannah River Site's Tank 48 waste, is not intended to be leach-resistant. In such cases, the intended permanent disposal site does not require the solidified product to perform "as good as glass." Indeed, the carbonate product is quite (typically over 50 wt%) soluble in water.

Table C-1 Summary of selected FBSR research and demonstration programs (adapted from SRNL-ORNL-PNNL-WRPS downselect (Jantzen [Jantzen 2015a]).

Facility	Scale	Radioactive or Non-Radioactive?	FBSR Bed Diameter, inches	Externally or Autothermaly Heated?	Dual or Single Reformer	Reductant	Catalyst?	Waste
INL 1999-2002	Bench-scale	Non-Radioactive	3	External	Single	Various coals	No	INL SBW
Studsvik-Bechtel 2001	Pilot-scale		6	internal	Single	Charcoal	No	Hanford LAW
INL 2001-2002	Pilot		6	External and autothermal	Single	BB charcoal	Yes	AN-107
SAIC-STAR 2003-2004	Pilot		6	External and autothermal	Single	BB charcoal	No	INL SBW Rassat LAW
TTT ESTD 2006	Engineering		15	Autothermal	Dual	Bestac coal	Yes	INL SBW
TTT ESTD 2008	Engineering		15	Autothermal	Dual	Bestac coal	Yes	WTP-SW (*Module A*)
SRNL BSR 2009	Bench-scale	Radioactive and Non-Radioactive	2.75	External and autothermal	Dual	Bestac coal	No	WTP-SW (*Module A*)
START OF THE DOE-EM WFQ PROGRAM								
TTT ESTD 2008	Engineering	Non-Radioactive	15	Autothermal	Dual	Bestac coal	Yes	Rassat LAW (*Module B*)
SRNL BSR 2010-2011	Bench-scale	Radioactive and Non-Radioactive	2.75	External and autothermal	Dual	Bestac coal	Some tests	Rassat LAW (*Module B*) SX-105 (*Module C*) AN-103 (*Module D*)
SRNL BSR 2011	Bench-scale	Non-Radioactive					Yes	AZ-101/ AZ-102 (*Module E*)
Pilot Testing Support for IWTU								
TTT ESTD 2016+	Engineering	Non-Radioactive	12 and 18	Autothermal	Single	Bestac coal	No	INL SBW
WTP-SW = WTP Secondary Waste; tested to show that FBSR can retain Tc from the melter off-gas. Rassat LAW was made by shimming actual SRS LAW to composition similar to Rassat 67 tank blend. The SX-105, AN-103, and AX-101/AZ-102 blends were actual Hanford LAW.								

The full-scale Integrated Waste Treatment Unit (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 fluidized bed IWTU system is similar in some ways to the prior fluidized bed calcination facilities at INL – the Waste Calcining Facility (WCF) and New Waste Calcining Facility (NWCF) that had been used since the 1980's to solidify high level waste (HLW) and SBW at the INL. The NWCF was replaced by the IWTU largely because (a) the (at the time) new Hazardous Waste Combustor (HWC) Maximum Achievable Control Technology (MACT) standards reduced regulatory limits for mercury, CO, and total hydrocarbons to levels below what the NWCF could achieve without modification, and (b) the NWCF emitted NO_x in large enough concentrations that, while still regulatorily compliant, caused a highly visible brown plume that raised public concern and dissent to continued NWCF operation (Boardman 2001, Soelberg 2003). The IWTU is designed to easily comply with the HWC MACT standards and also destroy NO_x to levels both regulatorily compliant and low enough to prevent the visible brown plume (TTT 2007b).

The IWTU is a first-of-a-kind, full-scale demonstration of steam reforming technology and processes. Much of the ITWU system and subsystems including waste feed, the steam reformer vessel referred to as the Denitration Mineralizing Reformer [DMR], off-gas system components, and solids handling processes are representative full-scale demonstrations of the same features of the FBSR system conceived for treating Hanford SLAW. 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 is highly soluble, because the IWTU carbonate product is highly soluble, is not correct.

WHAT IS MINERALIZING FLUIDIZED BED STEAM REFORMING

Steam reforming is broadly defined as a process in which superheated steam is used to crack and pyrolyze organic constituents, which in turn generates more free radicals that accelerate hydrocarbon compound decomposition and reactions with other solid and gaseous constituents. Radioactive liquid solutions such as Hanford LAW that contain dissolved nitrate/nitrite salts, mineral acids, alkali hydroxides, or residual organic solvents are chief candidates for steam reforming.

Figure C-1 summarizes chemical reactions that occur when a radioactive, nitrate-bearing liquid waste is atomized into the Denitration Mineralizing Reformer (DMR) vessel of the steam reforming process. The DMR contains a bed of particles that are the right size and density to be continually fluidized by a superheated flow of steam that enters at the bottom of the vessel. The steam is superheated to nominally 500-600°C prior to entering the DMR.

DMR Inputs and Outputs

Coal and oxygen are fed into the DMR where they react (also with some of the steam) to (a) heat the DMR to the target mineralizing operating temperature of around 725°C, and (b) produce H_2 and other reduced gas species such as CO and CH_4 that react with the nitrates and nitrites in the waste feed, converting the nitrates and nitrites to N_2 and H_2O. The coal and coal char can also react heterogeneously with some of the feed nitrates/NO_x. The coal and O_2 feedrates are metered so that the overall DMR process is stoichiometrically reducing to destroy hazardous feed organics and achieve efficient NO_x destruction on the order of 95-99%, with small residual amounts of reduced gas species including H_2, CO, and hydrocarbon gas species in the DMR outlet gas.

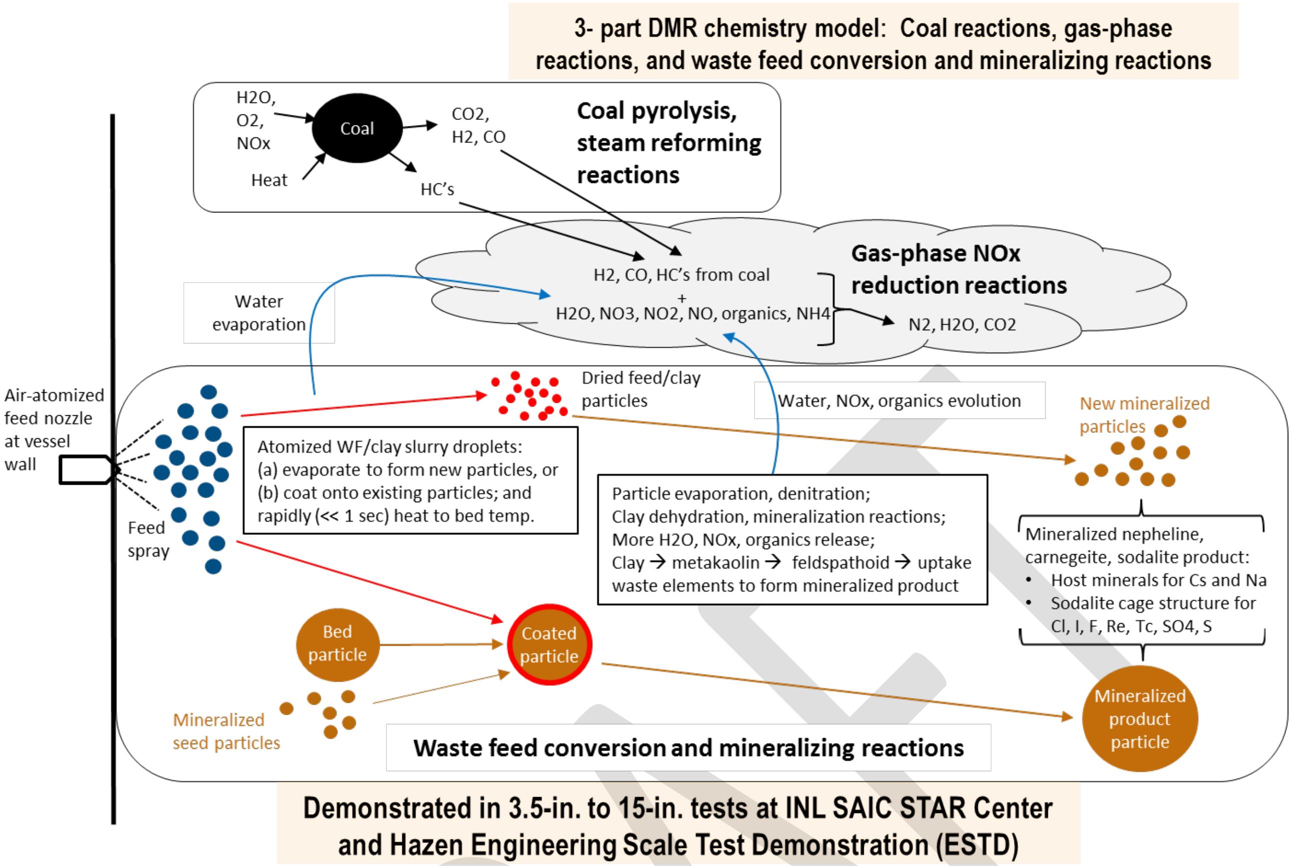


Figure C-1 Simplified three-part DMR chemistry model: coal reactions, waste feed conversion, and gas-phase reactions.

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 2015a]). The key ones are shown in Table C-2. This list is not exhaustive, nor does it show the carbon, hydrogen, hydroxyl and other ions and free-radical intermediate species, that along with the high mass and heat transfer rates and high gas-particle surface areas, make fluidized beds so effective at fast and efficient chemical reactions.

As a result of these heat generating, NO_x destruction, and organics pyrolysis reactions, the DMR outlet gas contains nominally on the order of:

- 65-70 vol% H_2O
- 10-15 vol% CO_2
- 10-15 vol% N_2
- 1-3 vol% H_2
- 1 vol% CO
- 0.5-1 vol% NO_x
- <0.1 vol% hydrocarbons
- <100 ppmv other gas species such as SO_2 and halogen gases

Table C-2. Heterogeneous solid-gas and homogeneous gas-phase reactions that occur under stoichiometrically reducing conditions during fluidized bed steam reforming.

$C + O_2 \rightarrow CO_2$ $C + \frac{1}{2}O_2 \rightarrow CO$	Coal oxidation reactions for autothermal heat generation
$C + H_2O \rightarrow CO + H_2$ $CO + H_2O \rightarrow CO_2 + H_2$	Water gas and water gas shift reactions that produce H_2, effective in NO_x destruction
$NO_3 + 2C \rightarrow NO + 2CO$ $NO_3 + C \rightarrow NO_2 + CO$ $2NO_3 + 4C \rightarrow N_2 + 2CO + 2CO_2$ $2NO_2 + 3C \rightarrow N_2 + 2CO + CO_2$ $2NO + 2C \rightarrow N_2 + 2CO$ $2NO + 2CO \rightarrow N_2 + 2CO_2$ $2NO + 2H_2 \rightarrow N_2 + 2H_2O$	Nitrate and NO_x destruction reactions
$C_xH_y + xH_2O \rightarrow xCO + (x+y/2)H_2$ $C_xH_y + (2x-y/2)H_2 \rightarrow xCH_4$	Waste organics pyrolysis reactions
$2CO + O_2 \rightarrow 2CO_2$ $2H_2 + O_2 \rightarrow 2H_2O$ $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	Other CO, H_2, and hydrocarbon oxidation reactions

The DMR stoichiometry is controlled by controlling the coal and oxygen inputs to autothermally generate the heat needed for the DMR process that operates at about 725°C, and destroy the nitrates, nitrites, NO_x, and waste feed organics, while also minimizing the amount of reduced gas species H_2, CO, and hydrocarbons. Most of the carbon content of the coal is fully oxidized to CO_2 and H_2O, needed to heat the DMR.

The waste feed is premixed with kaolin clay prior to being fed as a slurry into the DMR. Kaolin clay is commercially available and widely used in industrial and commercial uses such as manufacture of porcelain bathroom 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 waste feed slurry is atomized using air or N_2 atomization through the vessel wall directly into the hot fluidized bed. The atomized waste feed evaporates in less than 1 second as the waste feed 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 N_2, CO, CO_2, hydrocarbon gases, and H_2O (and S and halogen gases if the organics contain those elements). Any Hg in the LAW volatilizes into the process gas and must be controlled downstream to meet applicable Hg emission limits.

The remaining components of the SLAW (Na and lower-concentration elements including hazardous metals and radioactive elements) react with the clay to form the target mineralized waste form. These reaction products coat onto existing bed particles or form new bed particles. Fines elutriate from the fluidized bed and are captured in the Process Gas Filter (PGF).

The mineralized product can exit the DMR when bed particles are removed from the DMR, or when attrited fines elutriate from the DMR with the process gas, and are captured in the PGF.

DMR Design and Operating Features

These reaction processes are aided by the design and operation of the fluidized bed, which provides rapid gas-solid mixing and high particle surface areas which are stages for heterogeneous reactions. Figure C-2 illustrates a fluidized DMR vessel. Primary features include:

- Haynes 556 alloy or equivalent for strength and corrosion tolerance at temperatures ~725^{o}C (no refractory).
- 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 waste feed nitrates, nitrites, and organics.
- N_2, O_2, or air – atomized liquid/slurry waste feed 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.

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 different from the IWTU design.

The Mineralizing Process

The mineralizing process begins with the kaolin clay ($Al_2Si_2O_5(OH)_4$) added to the waste feed (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015]). The clay particles dehydrate as the OH$^{\bullet}$atoms are lost when the WF is heated above 550°C after WF injection into the DMR (Figure C-3). This causes the aluminum atoms to become charge-imbalanced and the clay becomes amorphous (loses its crystalline structure) and very reactive. This amorphous clay is called meta-kaolin. As the figure shows, the metakaolin can further evolve to feldspathoids[68]. Being charge-imbalanced, the metakaolin also readily reacts with cations in the salt waste such as Na to form nepheline ($NaAlSiO_4$ with hexagonal symmetry) and carnegieite (nominally $NaAlSiO_4$ with orthorhombic symmetry). Nepheline can further react with the waste to form sodalite(s) where the Na is exchanged with other cations such as Cs or K, and which provides a "cage" that can enclose a variety of waste anions. The resulting minerals include:

[68] Nepheline, sodalite, and nosean are known as the feldspathoid minerals. Feldspathoid minerals and zeolites, including the sodalite and nosean, are a large and diverse classes of minerals characterized by a crystalline framework of tetrahedral Al and Si with a three-dimensional pore system that can accommodate a variety of anions. The common theme in sodalite group minerals is the flexible framework structure that can expand to enclathrate various guest anions by cooperative changes in the Al-O-Si bond angle. (Pauling 1930). Sodalites are classified as "clathrasils," which are structures with large polyhedral cavities with "windows" in the cavity too small to allow the encaged polyatomic ions and/or molecules to pass through once the structure is formed (Liebau 1983, Mattigod 2006). Sodalites differ from zeolites in that the zeolites have tunnels or larger polyhedral cavities interconnected by windows large enough to allow diffusion of the guest species through the crystal.

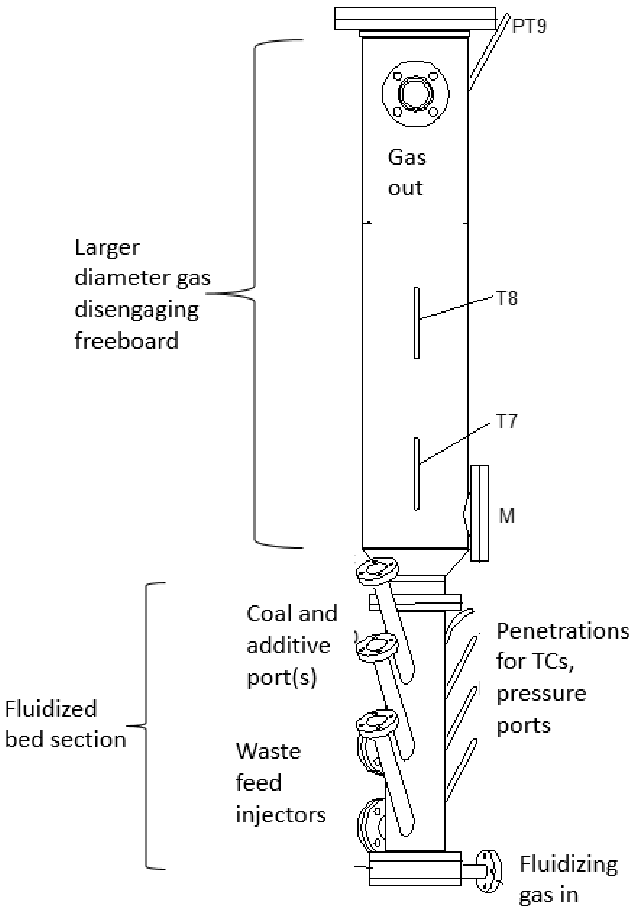


Figure C-2 Illustration of a fluidized DMR vessel (from Olson 2004a).

- Nepheline (nominally $NaAlSiO_4$).
- Sodalite (nominally $M_8(Al_6Si_6O_{24})X_2$, where M is an alkali cation such as Cs, K, Na, etc.—and X is a monovalent anion or a monovalent or divalent oxyanion, such as Br-, Cl-, I-, TcO_4-, ReO_4-, SO_4-2, etc.).
- Nosean (nominally $Na_8[AlSiO_4]_6SO_4$ with a larger cubic sodalite structure).
- Carnegieite (nominally $NaAlSiO_4$ of orthorhombic symmetry).

These nephelines and sodalites are the same mineral phases that have been developed as target mineral phases for not only FBSR mineral products but also high level waste (HLW) ceramic and glass bonded sodalite waste forms (Table C-3). Additions of kaolin clay form the desired sodalite and nephelines in a similar manner to the way in which glass formers are added to waste to form a borosilicate glass. The minerals offer atomic bonding of the radionuclides and hazardous metals comparable to glass, at higher Na_2O and SO_4^{-2} waste loadings than glass. The higher FBSR Na_2O and SO_4^{-2} waste loadings contribute to low disposal volumes and theoretically provide for more rapid processing of the LAW.

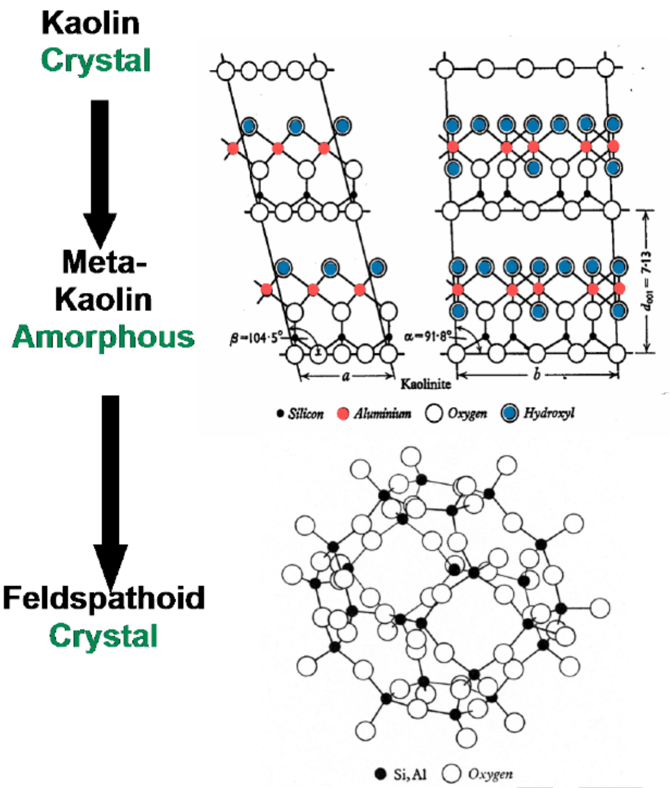


Figure C-3 Conversion of kaolin clay to reactive, amorphous meta-kaolin and to feldspathoid crystals during steam reforming (from Grimm 1953 and SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

Table C-3. Comparison of target mineral phases formed FBSR, HLW ceramic waste forms, and glass-bonded sodalite waste forms (from SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

Mineral Phases Formed in FBSR at ~700°C (Jantzen 2002, McGrail 2003b)	**Mineral Phases Formed in HLW Ceramic Waste Forms** (Barney 1974, Hatch 1953, Hench 1981, Hench 1986, Lutze 1988, Lee 2006, Laurant 2009, Donald 1997, Donald 2010, Stephanovsky 2004, NRC 2011)	**Mineral Phases in Glass Bonded Sodalite Waste Forms** (Moschetti 2000, Sinkler 2000, Ebert 2002a, Ebert 2002b)
Nosean-Sodalite $(NaAlSiO_4)_6(Na_2SO_4)$	Sodalite $(NaAlSiO_4)_6(NaMoO_4)_2$	Sodalite $(NaAlSiO_4)_6(NaI,NaCl)_2$
Nepheline $NaAlSiO_4$	Nepheline $NaAlSiO_4$	Nepheline $NaAlSiO_4$
Cubic Nepheline $NaAlSiO_4$	-	NaCl
Corundum Al_2O_3	Corundum Al_2O_3	PuO_2
Hematite Fe_2O_3	-	-
Magnetite Fe_3O_4	-	-

Feldspathoid mineral structures that represent the kinds of desired mineral forms in the durable, leach-resistant waste form are shown in Table C-4. These nepheline, carnegieite, sodalite, and nosean structures can incorporate the nonvolatile and semivolatile elements in the waste feed either into the mineral structure (nepheline/carnegeite) or inside “cages” (sodalites/nosean) of suitable sizes that contain some of key halogens and radionuclides (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

Table C-5 shows oxidation states and atomic radii for anions that can be captured inside the sodalite crystalline cage structures.

How Fluidized Bed Steam Reforming Would Treat Hanford Supplemental LAW

The Supplemental LAW treatment system feed vector is expected to vary widely and presents flowrate and composition challenges for the SLAW treatment process. Table C-6 summarizes monthly feedrate and composition data along with the “turndown ratio” that is used to describe the month to month variability. The feedrate turndown ratio is the ratio of the maximum monthly flowrate divided by the minimum monthly flowrate ratio.

The feedrate turndown ratio is a challenge that 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 waste feed delay storage to reduce the turndown from over 50x.

Table C-4. Substitutional cations and oxy-anions in feldspathoid structures (from SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

Nepheline – Kalsilite Structures*	**Carnegieite Structures**	**Sodalite Structures****	**Nosean Structures**
$Na_xAl_ySi_zO_4$ [Deer 2004] *where x=1-1.33, y and z = 0.55-1.1(H)*	$NaAlSiO_4$ high carnegieite (C) [Smith 1957; PDF #11-221]	$[Na_6Al_6Si_6O_{24}](NaCl)_2$ [Deer 2004, Brenchley 1994, Fechtelkord 2000]	$[Na_6Al_6Si_6O_{24}](Na_2SO_4)$ [Deer 2004, Gesing 1998, Deer 1963]
$NaAlSiO_4$ [PDF #052-1342; Nayak 1998] (O)^t	$NaAlSiO_4$ low carnegieite [Smith 1957; PDF #11-220 no symmetry given]	$[Na_6Al_6Si_6O_{24}](NaFl)_2$ [Deer 2004]	$[Na_6Al_6Si_6O_{24}](Na_2MoO_4)$ [Deer 2004, Brookins 1984]
$KAlSiO_4$ [Deer 2004]	$Na_{1.45}Al_{1.45}Si_{0.55}O_4$ [Thompson 1998a and 1998b]	$[Na_6Al_6Si_6O_{24}](NaI)_2$ [Babad 1980, Deer 1963]	$[Na_6Al_6Si_6O_{24}]((Ca,Na)SO_4)_{1-2}$ [Dana 1932]
$K_{0.00}Na_{1.00}AlSiO_4$ to $K_{0.25}Na_{0.75}AlSiO_4$ solid solution [Deer 2004]	$Na_{1.95}Al_{1.95}Si_{0.05}O_4$ [Thompson 1998a and 1998b]	$[Na_6Al_6Si_6O_{24}](NaBr)_2$ [Deer 1963]	$[(Ca,Na)_6Al_6Si_6O_{24}]((Ca,Na)S,SO_4,Cl)_x$ [PDF^f #17-749]
$(Na_2O)_{0.33}NaAlSiO_4$ [Klingenberg 1986] (C)	$Na_{1.75}Al_{175}Si_{0.25}O_4$ [Thompson 1998a and 1998b]	$[Na_6Al_6Si_6O_{24}](NaReO_4)_2$ [Mattigod 2006]	
$CsAlSiO_4$ [Deer 2004]	$Na_{1.65}Al_{165}Si_{0.35}O_4$ [Thompson 1998a and 1998b]	$[Na_6Al_6Si_6O_{24}](NaMnO_4)_2$ [Barrer 1945, Srdanov 1994]	
$RbAlSiO_4$ [Deer 2004]	$Na_{1.55}Al_{155}Si_{045}O_4$ [Thompson 1998a and 1998b]	$[NaAlSiO_4]_6(NaBO_4)_2$ [Buhl 1989, Tobbens 2000]	
$(Ca_{0.5},Sr_{0.5})AlSiO_4$ [Deer 2004]	$Na_{1.15}Al_{115}Si_{085}O_4$ [Thompson 1998a and 1998b]	$(Fe,Zn,Mn)_4[Be_3Si_3O_{12}]S$ [Deer 1963]	
$(Sr,Ba)Al_2O_4$ [Deer 2004]	$Na_3MgAlSi_2O_8$ [Thompson 1998a and 1998b]	$Sr_8[Al_{12}O_{24}](CrO_4)_2$ [Depmeier 1987]	
$KFeSiO_4$ [Deer 2004]		$Na_8[AlSiO_4]_6(SCN)_2$ [Buhl 2001]	
$(Na,Ca_{0.5})YSiO_4$ [Barrer 1945]		$Na_6Al_6Si_6O_{24}$ (Zeolite A) [Campbell 2000, Shannon 2000]	
$(Na,K)LaSiO_4$ [Barrer 1945]		$Na_8[ABO_4]_6{\cdot}X_2$, where A=Al and Ga, B=Si and Ge, and X includes Cl^-, Br^-, I^-, $(ClO_3)^-$, $(BrO_3)^-$, $(HCOO)^-$, $(MnO_4)^-$, $(SCN)^-$ and $(SeCN)^-$ [Fleet 1989, Johnson 2000]	
$(Na,K,Ca_{0.5})NdSiO_4$ [Barrer 1945]		$Na_{7.50}Fe^{2+}_{0.05}[Si_{6.07}Al_{5.93}]O_{24}Cl_{1.99}(SO_4)_{0.01}$ (hackmanite) [Peterson 1983]	

* Iron, Ti^{3+}, Mn, Mg, Ba, Li, Rb, Sr, Zr, Ga, Cu, V, and Yb all substitute in trace amounts in nepheline, [Deer 2004].

** Higher valent anionic groups such as AsO_4^{3-} and CrO_4^{2-} form Na_2XO_4 groups in the cage structure where X= Cr, Se, W, P, V, and As [Barrer 1945].

f Powder Diffraction File

t May be low-carnegieite per original reference.

(C) is for cubic crystal symmetry, (H) is for hexagonal crystal symmetry, (O) is for orthorhombic crystal symmetry.

Table C-5 Oxidation states and atomic radii for common anions incorporated into the sodalite framework (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

Element/ species	Mineral Name	Oxidation State	Coordination Number	a (Å)	Space Group	Ionic Radius (Å) (Pierce 2012)	Ionic Radius (Å) (Taylor 1978)
F^-	F-sodalite	-1	VI	NM	P43n	1.33	-
Cl-	Cl-sodalite	-1	VI	8.8835	P43n	1.81	1.78
ClO_4^-	Cl-sodalite	-1	VI	8.8835	P43n	2.40	-
SO_4^{2-}	Nosean	+6	VI	9.0932	P43n	2.30	2.37-2.57
TcO_4^-	Tc-sodalite	+7	VI	NM	P43n	2.52	-
ReO_4^-	Re-sodalite	+7	VI	9.1528	P43n	2.60	-
I^-	I-sodalite	-1	VI	9.0027	P43n	2.16	2.14-2.17
Br^-	Br-sodalite	-1	VI	NM	P43n	1.95	1.93
OH^-	Hydroxy-sodalite	-1	VI	8.89	P43n	1.36	1.48-1.51
NO_3^-	Nitrated-sodalite	-1	VI	8.978	P43n	2.00	-
NM=Not Measured							

Table C-6. 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**	turndown ratio; lag tank needed to achieve turndown ratio of ~2 per FBSR
WTP LAW vitrification feedrate, gpm	3.4	1.8	dy flowrate presumably by design
Solids concentration, wt%	3.3	126	elevant to FBSR which has much more added clay per L waste
Na concentration, g/L	180	2	clay as needed
NO_3 concentration, g/L	110	6	royed by FBSR system
NO_2 concentration, g/L	30	11	
Hg concentration, mg/L	3.0	55	l Hg control but necessary DF decreases after ~2035
Tc-99 concentration, mg/L	3.2	36	ured 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	Not relevant		royed by FBSR system
The monthly turndown is the ratio of the maximum monthly flowrate (or concentration) divided by the minimum monthly value.			

FBSR PROCESS FLOW OPTIONS AND DIAGRAMS

Two FBSR options are proposed, based on the desired waste form. Treatment Option 3, the Steam Reforming Base Case (Figure C-4) 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. Secondary wastes in this option (spent filters, equipment, PPE, etc.) are also disposed in IDF. Treatment Option 3b, Steam Reforming to WCS (Figure C-5) 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 3_ (Figure C-6) 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.

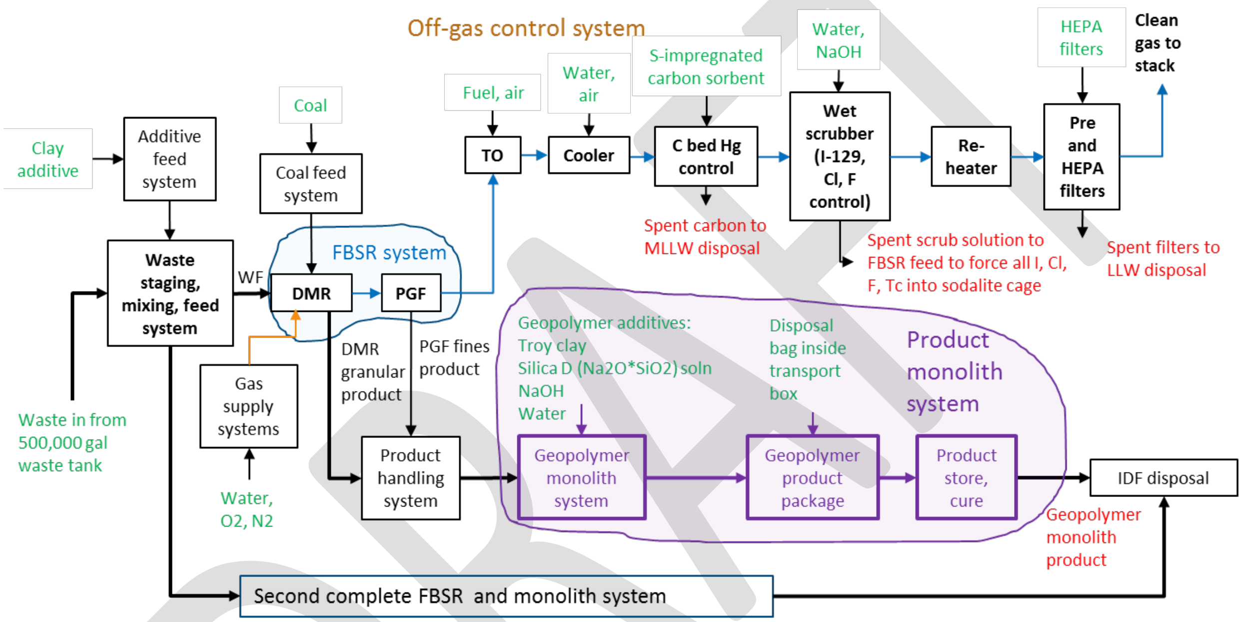


Figure C-4 Base Case Mineralizing FBSR (Treatment Option 3): Two DMR systems; solid monolith product disposed at IDF (secondary wastes also disposed at IDF).

Figure C-7 shows that the very highest sustained waste feedrates occur in about the first three years of SLAW treatment operations. After those first three years, the feedrate varies by over 50x turndown ratio. Both FBSR options include the following features that are driven by the high, sustained initial waste feedrate, and the 50x turndown ratio that occurs during the entire life of the facility.

- Utilize 500,000 gal waste holding tank upstream of the SLAW treatment system.
- Two 50,000 gal WF Hold tanks to provide time for filling and sample analysis prior to mixing with 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.

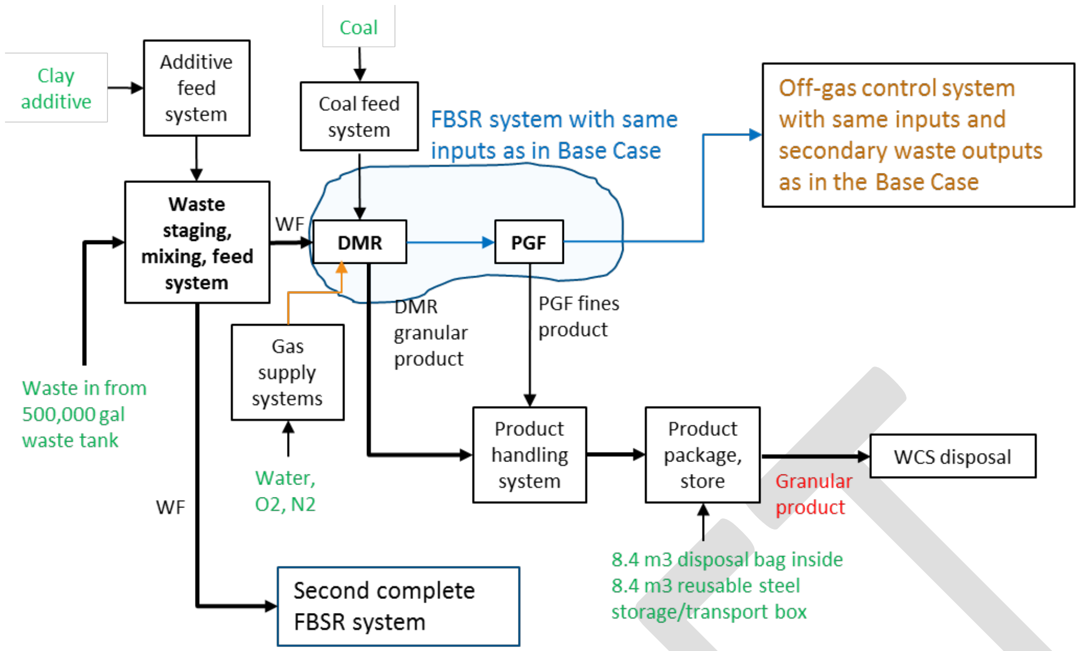


Figure C-5 Treatment Option 3b, Steam Reforming to WCS: Two DMR systems; granular solid product (secondary wastes also disposed at WCF).

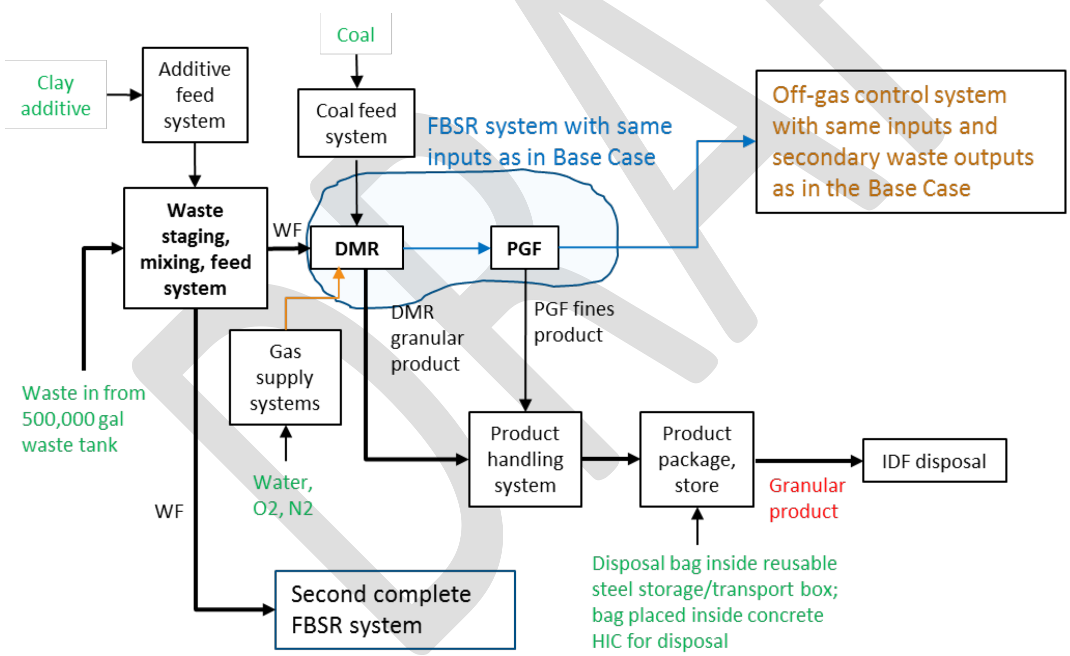


Figure C-6 Treatment Option 3_, Steam Reforming to WCS: Two DMR systems; granular solid product disposed at IDF inside concrete HICs (secondary wastes also disposed at IDF).

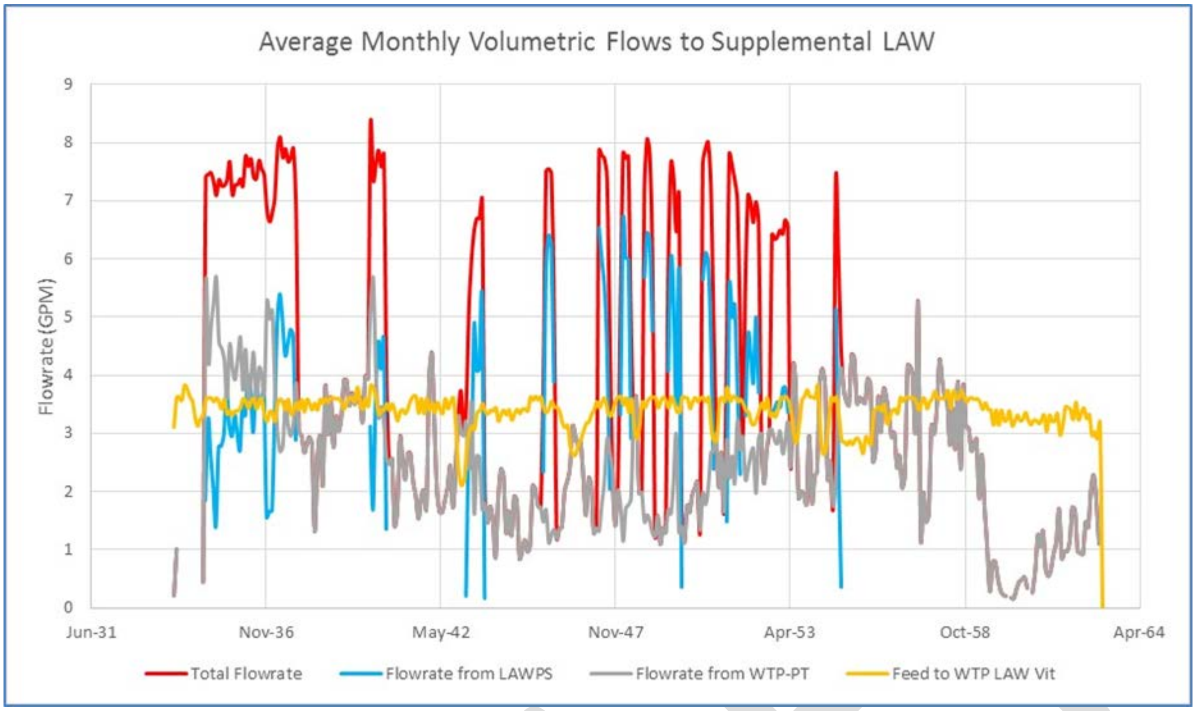


Figure C-7 Variation in the monthly Hanford LAW stream flowrates from the feed vector.

The figures show that the core DMR and PGF are actually only two of many components that comprise the feed systems, DMR system, off-gas system, and product handling system. While these boxes in the figure are not drawn to scale, the figure indicates that the core DMR and PGF represent only a fraction of the entire facility footprint.

The size and configuration of the DMR was estimated based on the average, minimum, and maximum 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% higher than the IWTU diameter of 4 ft, based on scaling the cross section areas according to the volumetric feedrate (1.75 times greater than the 2.5 gpm IWTU feedrate).

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

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

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

Figure C-8 shows a concept design for the WF system for the purposes of this evaluation. 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). This nominal 50,000 gallon tank, together with the 500,000 gal tank farm tank, and two 30,000 gal

Mix/feed 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. Each WF Hold Tank can feed to either or both Mix-feed tanks, and either Mix-feed Tank can feed to either or both DMRs. The delivery system from each of the WF Hold tanks and Mix-feed tanks 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.

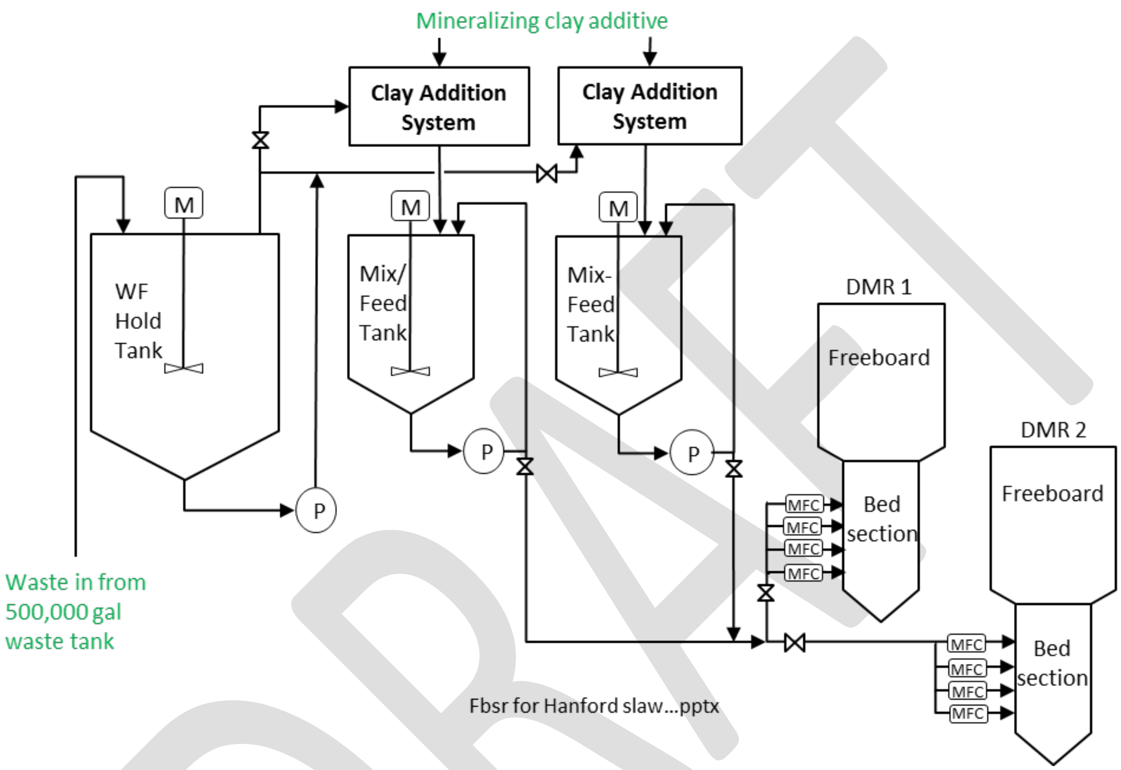


Figure C-8 Conceptual FBSR WF system.

Commercially available, fine-particle-size clay (such as is shown in Figure C-9) is added in a Clay Addition System for each Mix-feed Tank (such as is shown in Figure C-10). Dry 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 correct proportion of 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. Each DMR would have four feed nozzles oriented 90 degrees from each other around the circumference of the bed section. 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-9 Typical commercially available clay.

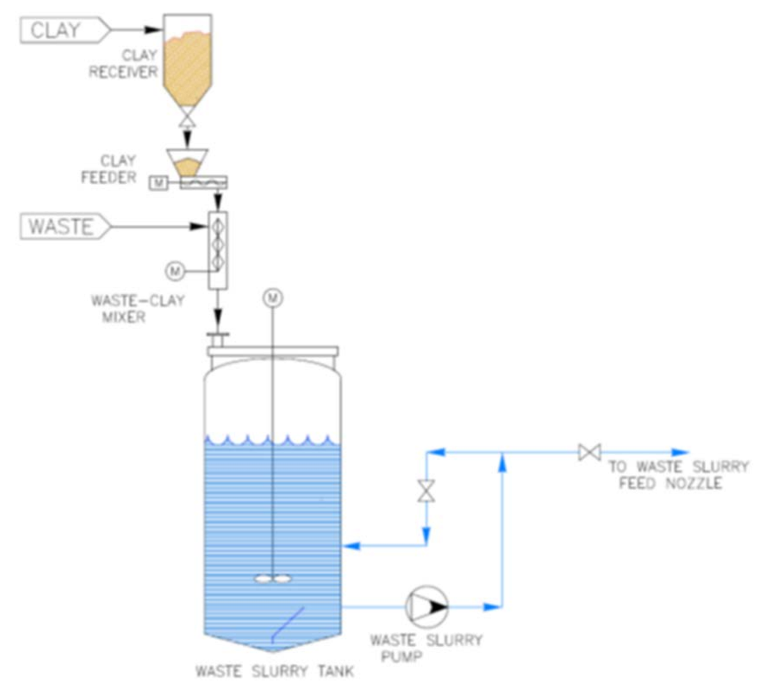


Figure C-10 Clay and waste high shear in-line mixing system concept design.

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 C-11. 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 2009b), and the FBSR mineral waste form downselect report (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

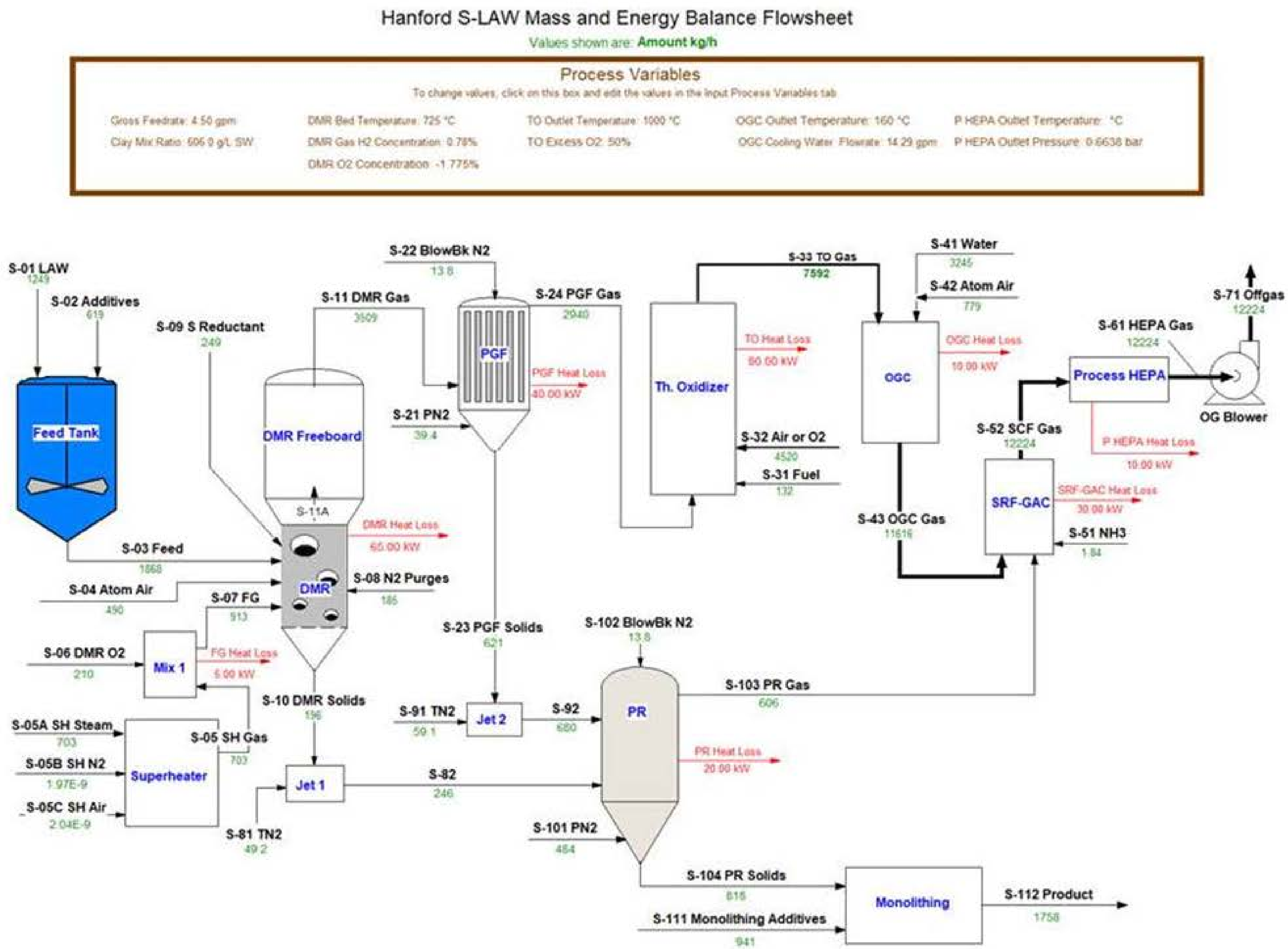


Figure C-11 Mass and energy balance for the average feed vector.

This mass and energy balance includes determination of the amount of coal (249 kg/hr) added to the DMR to heat the DMR (to 725°C), evaporate the liquid in the WF, and heat the WF to the DMR temperature, and provide the pyrolysis conditions for WF organics and NO_x destruction. 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 and converted to CO_2, H_2O, H_2, CO, gasified hydrocarbons, mainly CH_4, and SO_x. Most (about 90%) of this reacted coal is converted to CO_2 and H_2O; only about 10% is converted to H_2, CO, and gasified hydrocarbons to produce sufficiently reducing stoichiometry to destroy the nitrates, nitrites, NO_x, and waste feed hydrocarbons.

The coal used for the IWTU was specified to be a unique low-S, low-ash, low-moisture, low-volatiles precalcined coal (Table C-7) procured overseas because this precalcined coal is not presently produced in the U.S. 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%. Other coals including un-calcined coal from various sources have also been tested successfully; coal that would be demonstrated for successful use for SLAW treatment should be assumed to be a commonly available coal in the U.S.

Table C-7 Specifications of coal used in the IWTU fluidized bed steam reforming process (from Jantzen 2015b).

Parameter	How Measured	As-Received Specifications		
		Min	**Preferred**	**Max**
Oxidation initiation in air, °C	Thermal gravimetric analysis (TGA)	300	350	400
95% oxidation in air, °C		None	650	700
Volatiles, wt%	Proximate analysis, wt% (ASTM D3172)	10	15	20
Ash, wt%		0	5	10
Moisture, wt%		0%	<5	9
Sulfur, wt%	Ultimate analysis (ASTM 3176)	0	0.35	0.7
Higher heating value, Btu/lb	ASTM D5875	11,500	> 12,500	None
Average particle Size, mm	Sieve Analysis (ASTM D4749)	6	10	12
Ash CaO, wt%	Ash analysis (ASTM D2795)	0	<2	5
Ash K2O + Na2O, wt%		0	<2	3
Ash SiO_2, wt%		0	<60	65

Figure C-12 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. This could be reduced to about 0.8 kg (1 L) if the amount of incompletely reacted coal could be reduced.
- ~1.9 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.
-

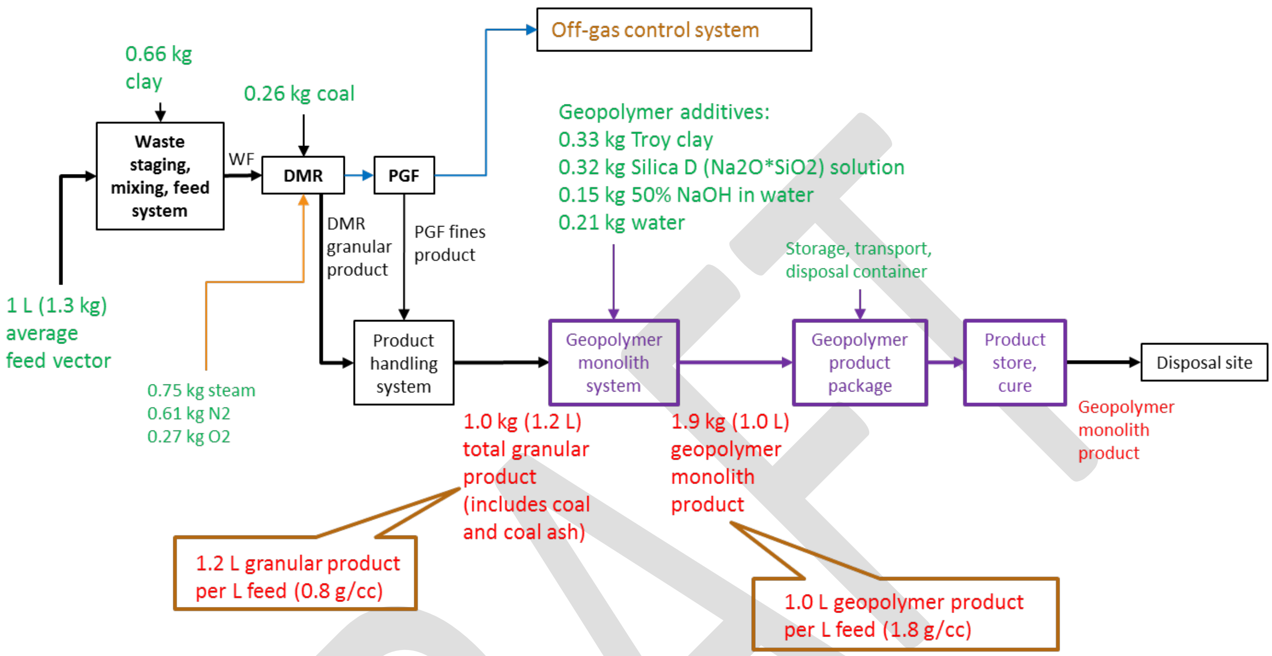


Figure C-12 Initial mass balance results for FBSR treatment of Hanford SLAW.

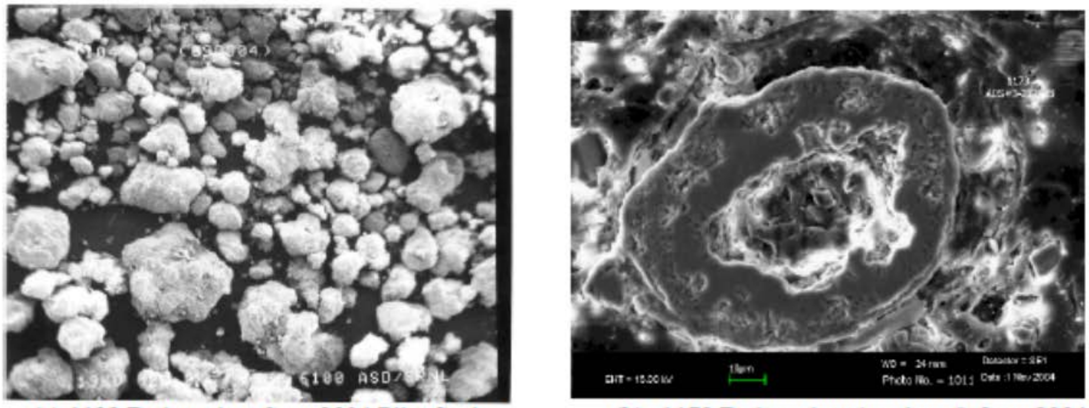
MINERAL WASTE FORMS

The mineral waste form produced from the mineralizing FBSR process was studied extensively between about 2002 to 2015. Results of these studies are reported in many individual documents, and also provided in the 2015 downselect report (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]). Much of the following description and performance of the FBSR mineral waste form and is extracted from the downselect report. This reference, and references of this reference, contain extensive additional detail.

Granular and Monolith Mineral Waste Forms

Figure C-13 shows scanning electron micrographs of the granular mineralized waste form such as would be produced in Treatment Option 3b, Steam Reforming to WCS. 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-14 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-13 Scanning electron micrographs of FBSR bed product from INL SBW; Science Applications International Corporation Science and Technology Applications Research (SAIC-STAR) 6 in. diameter FBSR (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

Figure C-14 Troy clay geopolymer monolith of Hanford LAW 60% FBSR product (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

Waste Form Mineralogy Control

Multiple test programs and studies have used the "MINCALC" process control strategy 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 clay additive, depending on the input feed composition, would be a choice of fine-particle-sized clays commercially available and commonly used for many processes including the manufacture of porcelain fixtures.

The amount and type of clay is determined based on the input LAW composition so that the combined mixture achieves the target composition range shown in the ternary diagram shown in Figure C-15. This diagram has 100% Na_2O at the lower left apex; 100% Al_2O_3 at the lower right apex; and 100% SiO_2 at the top apex. Various waste streams tested in bench, pilot, and engineering scale mineralizing steam reforming demonstrations are placed according to their original Na_2O – Al_2O_3 ratios along the bottom axis. Various commercial clays are located on the top-right axis according to their Al_2O_3 – SiO_2 ratios. The stoichiometrically desired Na_2O – Al_2O_3 – SiO_2 region in the ternary diagram is just off-center to the right of diagram. So the right clay, or mixture of clays, for each waste Na_2O – Al_2O_3 ratio, is determined by a straight line between that Na_2O – Al_2O_3 ratio on the bottom axis through the region of desired Na_2O – Al_2O_3 – SiO_2 stoichiometry, to the upper-right Al_2O_3 – SiO_2 axis. That point in the upper-right axis defines the approximate target Al_2O_3 – SiO_2 to obtain by the right selection or mixture of commercial clays.

The granular product is a heterogeneous mixture of the mineralized WF product, incorporated coal ash, and incompletely reacted coal particles. It can contain appreciable dispersible fines and it has a low bulk density with void spaces between particles. The Base Case includes the conversion of this low-density, somewhat compressible waste form with dispersible fines into a monolith which actually increases the density but not the volume, and most important, eliminates the dispersible fines and increases the compressive strength to exceed 500 psig. This enables the waste form to the compressive strength limit without having to use such containers as High Integrity Containers (HICs).

Alternatively, the granular product can be placed inside HICs such as metal or concrete containers or vaults to provide the needed compressive strength. The FBSR waste form performance ([a] ability to immobilize radioactive or hazardous constituents, and [b] durability [NRC 2011]) rather than HIC performance is the focus of this study.

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.

The downselect program studied monolith production using both fly ash and clay additives, along with added sodium silicate, to the granular mineralized product to produce a geopolymer monolith with an overall Na_2O – Al_2O_3 – SiO_2 stoichiometry similar to the target stoichiometry. The desired stoichiometry of the successfully-tested geopolymer monoliths are shown in Figure C-16; located in the Na_2O – Al_2O_3 – SiO_2 ternary diagram just to the left (higher Na_2O) and higher (higher SiO_2) than the original mineralized product stoichiometry.

Product Analyses and Durability Tests

This section contains information summarized from the FBSR mineral waste form downselect report (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]). 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

NRC 2011 goes on to say "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." This statement was based on the mineralized waste form results available prior to 2011. Since then, additional FBSR waste form testing has been performed, which adds to the pre-2011 body of data.

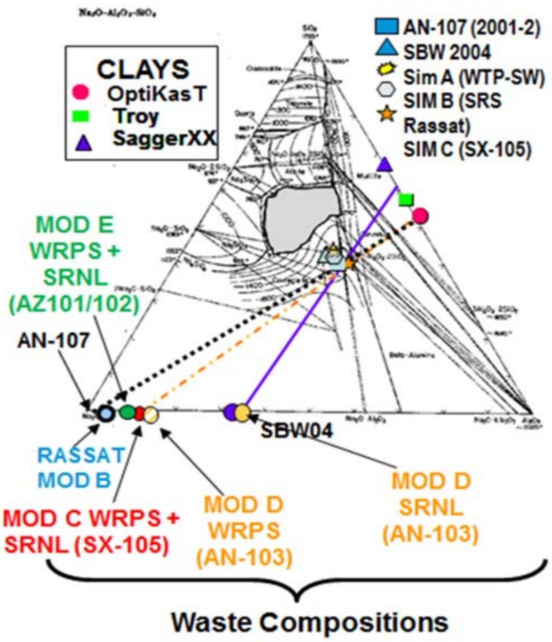


Figure C-15 Target MINCALC $Na_2O - Al_2O_3 - SiO_2$ composition for a durable mineralized product.

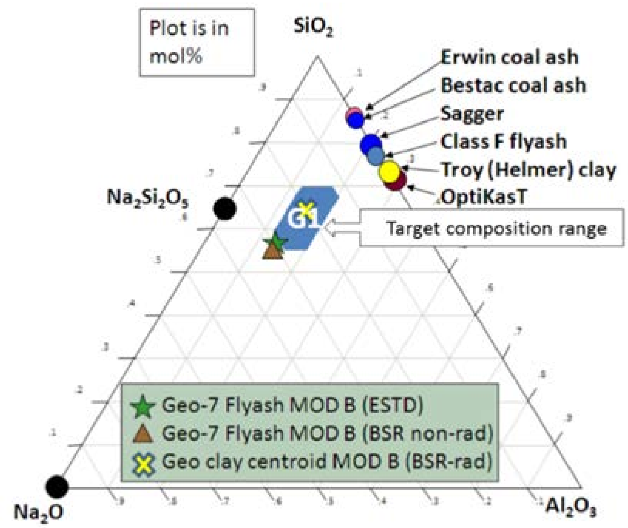


Figure C-16 $Na_2O - Al_2O_3 - SiO_2$ stoichiometries for selected fly ash and clay based geopolymers of mineralized products of Engineering Scale Test Demonstration (ESTD) and radioactive and non-radioactive bench scale reactor (BSR) tests.

NRC 2011 further finds that “There is a need to demonstrate the application of current tests to new waste forms if they are to be used in the DOE-EM cleanup program,” and recommends the following candidate tests for multiphase oxide/mineral/metal waste forms such as the mineral FBSR product:

- ASTM C1220, “Standard Test Method for Static Leaching of Monolithic Waste Forms for Disposal of Radioactive Waste” (applicable only to monolithic waste forms).
- ASTM C1285 “Standard Test Methods for Determining Chemical Durability of Nuclear, Hazardous, and Mixed Waste Glasses and Multiphase Glass Ceramics: The Product Consistency Test (PCT).”
- ASTM C1662 “Standard Practice for Measurement of the Glass Dissolution Rate Using the Single-Pass Flow-Through Test Method.”
- ASTM C1663 “Standard Test Method for Measuring Waste Glass or Glass Ceramic Durability by Vapor Hydration Test.”
- Pressure Unsaturated Flow-through Test (PUF).
- ASTM C1308 (“Standard Test Method for Accelerated Leach Test for Diffusive Releases from Solidified Waste and a Computer Program to Model Diffusive, Fractional Leaching from Cylindrical Waste Forms”) or ANSI 16.1 (“Measurement of the Leachability of Solidified Low-Level Radioactive Wastes by a Short-Term Test Procedure”) or EPA 1315 (“Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials using a Semi-Dynamic Tank Leaching Procedure”).

The SRNL-ORNL-PNNL-WRPS downselect studies performed a thorough and rigorous evaluation to select from this list the performance tests that are expected to be required to demonstrate that the mineralized product from FBSR can be permanently disposed in the Hanford IDF (Jantzen 2015a). These tests need to demonstrate that the mineralized waste form would meet requirements of the waste disposal facility (Burbank 2002, Qafoku 2011, and US NRC 1991), the Hanford WTP contract (DOE/ORP 2000), DOE Order 435.1, and permit requirements established by Washington State Department of Ecology. The performance test results must also demonstrate to various stakeholders including DOE ORP, WA Department of Ecology, Hanford Advisory Board, local Native American tribes, and the local public that the mineralized product is "as good as glass."

Table C-8 summarizes the performance tests determined to demonstrate if the mineralized waste form can meet these requirements. 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. Figure C-17 shows, in this "tie-back" strategy, how the radioactive and non-radioactive tests tie to each other.

In accordance with the recommendations from NRC 2011, the following recommended, current durability tests were demonstrated for both the granular and monolith waste forms:

- 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.

X-ray Absorption Spectroscopy (XAS) has 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 $Tc_2S(S_3)_2$; with equally low solubility during durability testing. TcO_2 is the same oxide species present in HLW waste glasses formed under slightly reducing flowsheets like the Defense Waste Processing Facility (DWPF).

The following sections summarize the performance test results from the SRNL-ORNL-PNNL-WRPS downselect studies. Considerably more detail, and references to the reports of the actual tests, are provided in Jantzen 2015a.

Table C-8 Summary of FBSR mineralized waste form studies (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

Pilot Scale Facility, date		FBSR diam..	Waste	Granular PCT Testing	TCLP of Granular Form	Granular SPFT Testing	Preliminary Risk Assessment	Product Tested	Coal	PSD	MonoLith	Monolith PCT Testing	Monolith SPFT Testing	Monolith ANS 16.1/ ASTM C1308 Testing	TCLP of Monolith
adioactive Testing															
HRI/TTT 12/2001 Jantzen 2002		6	LAW Env. C AN-107	Jantzen 2004	Jantzen 2002, 2004	McGrail 2003a, 2003b, and PUF testing, Pierce 2007	Mann 2003	Bed	Removed by hand	Gaussian	No	N/A			
		6		Pariezs 2005, Jantzen 2006a, 2006b		None	"Tie-back" Strategy **Error! Bookmark not defined.**	Fines	Removed by 525°C roas-ting						
SAIC/STAR 7/03 Soelberg 2004a, Marshall 2003		6	SBW			None	None	Bed			Yes (samples were combined; 20% LAW, 32 % SBW and 45% startup bed	Jantzen 2006c, 2007b	N/A		
SAIC/STAR 8/04 Olson 2004a		6	LAW Rassat			Jantzen 2006b, 2007; Lorier 2005, and PUF, Pierce 2012, 2014	Data from Ref Jantzen 2006b, 2007a; Lorier 2005, "Tie-back" Strategy **Error!**	Bed and fines separate							

							Bookmark not defined.								
SAIC/STAR 7/04 & 11/04 Olson 2004b		6	SBW			Lorier 2005, Jantzen 2006b	None								
HRI/TTT 12/06		15	SBW	Crawford 2007		None	None				No	N/A			
HRI/TTT 2008 THOR 2009b		15	LAW Rassat	Jantzen 2010, 2011, 2013; Crawford 2011, Evans 2012	Crawford 2011, Jantzen 2011, Evans 2012	Neeway 2012	"Tie-back" Strategy **Error! Bookmark not defined.**	Bed and fines to-gether	Not re-moved	Bi-modal	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		2.75	LAW Rassat	Jantzen 2012, 2013		Neeway 2012, 2013; and PUF, Neeway 2014, Willliams 2015	"Tie-back" Strategy **Error! Bookmark not defined.**	Bed and fines to-gether	Not re-moved	Gaussi an	Yes	Jantzen 2013	Neeway 2013	Jantzen 2013	
			WTP-SW	Crawford 2014, Jantzen 2012		None	None					Crawford 2014	None	Crawford 2014	

PCT – product consistency test method (ASTM C1285-08); SPFT – single pass flow-through test method (ASTM C1662); ANSI/ANS16.1/ASTM C1308/EPA 1315 – monolith immersion tests all similar with different leachate replenishment intervals; Pressure Unsaturated Flow-through Test (PUF); -LAW Env. – low activity waste envelope A, B, and C; PSD - particle size distribution; N/A – not applicable. Compressive strength tests were also performed on monolith samples, but not indicated in this table.

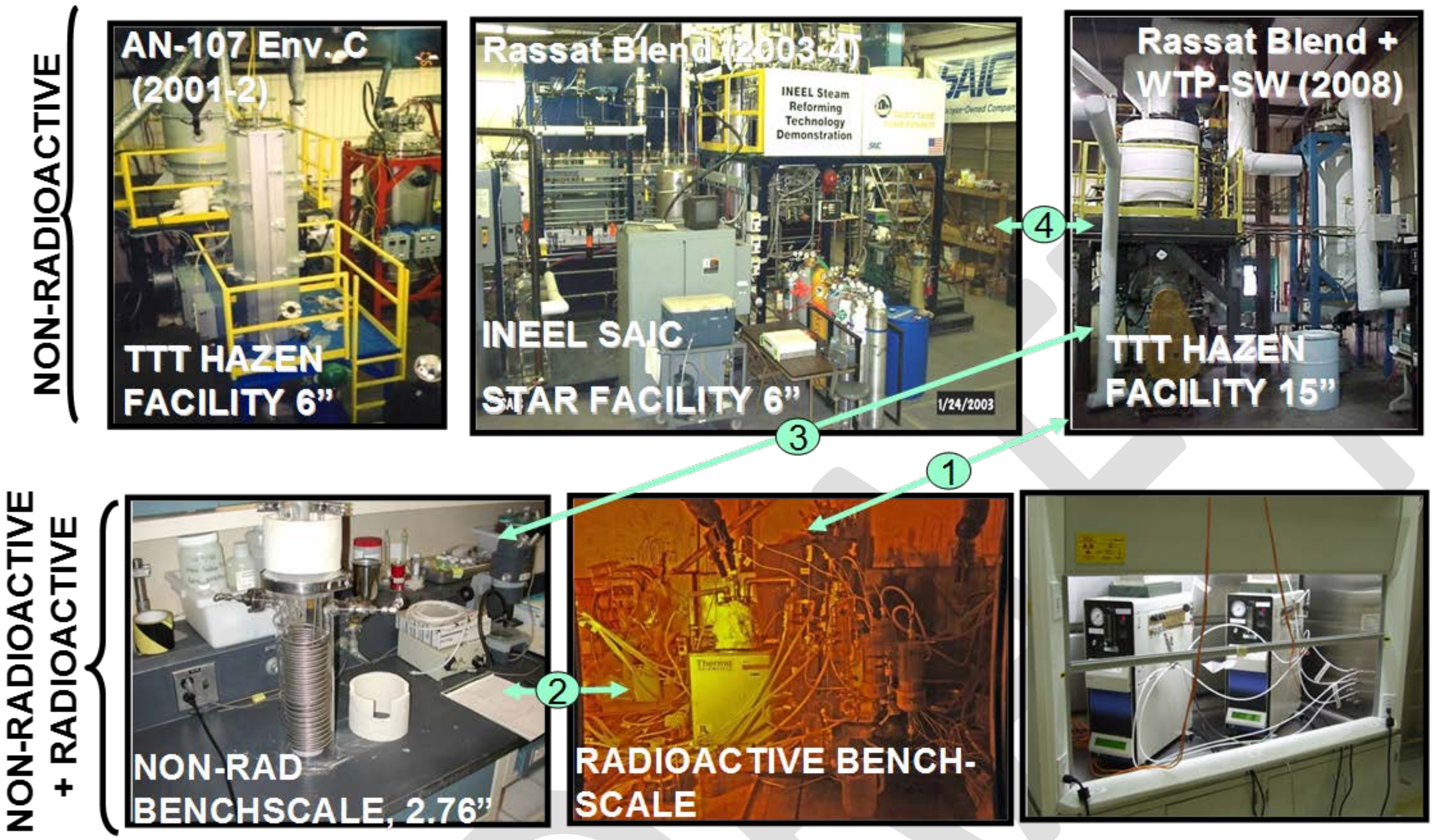


Figure C-17 Tie-back strategy between engineering scale non-radioactive pilot testing (top row) and BSR non-radioactive and radioactive testing (bottom row) (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]).

(Notes: In order of importance, tie-back #1 is between the radioactive BSR run with the Tank 50 waste shimmed to be like the Rassat Blend (this study) and the non-radioactive engineering scale Rassat Blend tested in 2008. Tie-back #2 is between the non-radioactive BSR testing with Rassat Blend simulant and the radioactive BSR testing with the Tank 50 waste shimmed to be like the Rassat Blend. Tie-back #3 is between the non-radioactive BSR and the non-radioactive pilot testing with the Rassat Blend simulant. Tie-back #4 is between the pilot scale testing performed at SAIC-STAR in 2004 and the pilot scale testing performed at HRI in 2008 with the Rassat Blend simulant. Note that the radioactive BSR controllers and data acquisition are in a radioactive hood and not in the shielded cells [bottom right photo]).

PCT Results

- No impact of product reducing – oxidizing ratio (REDOX) on durability in short and long-term PCT tests (except for Cr in TCLP, for which leachability can be controlled by adding some iron oxide to tie up the Cr in $FeCr_2O_4$).
- <2 g/m^2 leachable per PCT for granular product and monoliths (using geometric surface area, equivalent to vitreous WFs).
- <2 orders of magnitude lower than 2 g/m^2 if the Brunauer–Emmett–Teller (BET) surface area is used instead of the geometric surface area) for granular product.
- 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.
- Re is a good Tc surrogate for this waste form.
- Long-term PCT testing (1, 3, 6, and 12 month) at 90°C by ASTM C1285 has not shown any significant change in the mineral assemblages as analyzed by XRD.

SPFT Results

- Relatively low forward dissolution rate ~10^{-3} g/(m^{2}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 made in the BSR and in 15-in. pilot-scale 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 a different rate compared with the dissolution of the predominant nepheline phase.
- The 2.5-year-long PUF test results for 2004 6-in. pilot scale FBSR products were similar to results of the 1-yr BSR and 15-in. pilot plant product PUF test results.
- Elemental release rates and geochemical modeling suggest that Al and Na release was controlled by nepheline solubility, whereas Si release was controlled by amorphous silica solubility after being released from the Na_2O-Al_2O_3-SiO_2 (NAS) matrix.
- Similar Re and S releases suggests that their release is either from the same phase or from different phases with similar stability.
- Re release was an order of magnitude lower than Tc release [(2.1 ± 0.3) x 10^{-2} g/(m^{2}d)] from LAW AN102 glass.
- Geochemical calculations using PHREEQ-C on 200 day PUF data suggests the steadystate S and Re concentrations are within order of magnitude of solubility of phase pure nosean and Re-sodalite, respectively.

Re and S were released from a "mixed anion" sodalite phase (likely Re and SO_4-bearing), which has a different stoichiometry in comparison to the pure mineral end-members; and a thermodynamic stability between the pure phase end-members; such a solid solution is already known between the Cl and SO_4 sodalite/nosean endmembers and a mixed Re/Tc sodalite made at SRNL.

Tests performed on mineralized product monoliths are listed in Table C-9. Results of these monolith tests are summarized below (SRNL-ORNL-PNNL-WRPS downselect [Jantzen 2015a]):

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

Table C-9. Tests performed on monoliths.

MONOLITH	DRY BASIS FBSR LOADING (%)	COMPRESSIO N	XRD PHASES	PCT	ANALYZED CHEMICAL COMPOSITION	TCLP TESTING	BULK DENSITY	ANSI/ANS 16.1/ ASTM C1308	SPFT/PUF TESTING
Fly Ash GEO-7 ESTD LAW P-1B				-Term ong-Term					
Fly Ash GEO-7 Mod B Sim				-Term ong-Term					
Clay ESTD LAW P-1B									
Clay Mod B Sim									
Clay Mod B Rad				-Term[a]					
				Term[a]					

a) Both the 42% and 65% WL Mod B radioactive monoliths made with clay were tested with PCT. The lower 42% WL PCT leachates were archived and the 65% WL PCT leachates were analyzed and reported.
b) Chemical compositions calculated from analyzed granular products and Na, Al, and Si oxide compositions of the additives.

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-10.

Table C-10. Expected FBSR off-gas control performance requirements.

Parameter	Requirement or expected value	Basis
Stack gas NO_x concentration	$\leq$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	$\geq$99.99%	Assume bounding requirement is HWC MACT standards for principal organic hazardous constituents
Hg decontamination factor (DF)	$\geq$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	$\geq$97%	
HF capture efficiency	$\geq$97%	
I-129 capture efficiency	$\geq$99%	
Particulate capture efficiency	$\geq$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).

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. Also, 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.

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.

Table C-11 shows measured and estimated single-pass FBSR control efficiencies for elements that could be in FBSR waste feeds. This table includes single-pass control efficiencies measured in pilot and bench-scale tests. Single-pass control efficiencies have not been measured for all potentially relevant elements, so the table also shows how relative elemental volatilities as defined by the Environmental Protection Agency (EPA) and in other vitrification, used fuel reprocessing, and thermal process studies were used to estimate single-pass control efficiencies for elements not measured in pilot and bench-scale tests. Results of the pilot-scale tests are expected to be the most reliable for indicating performance of a full-scale FBSR system; followed by results of the bench-scale tests. The estimations of single-pass efficiencies from relative volatilities are least reliable. All of the measured and estimated single-pass control efficiencies for elements of greatest interest should be confirmed in full-scale demonstrations.

Table C-11. FBSR single-pass elemental capture

Element	Measured capture efficiency, %			EPA HWC MACT definition, Ref. 1	Relative volatility			Estimated or average capture efficiency, %
	Ref. 1	Ref. 2 min	Ref. 2 max		Ref. 3 (for melters)	Ref. 4 (for used fuel separations)	Ref. 5 (for thermal processes)	
Ac	---			---	---	NV	NV	99.96%
Ag	99.999%			---	---	NV	SV	---
Al	99.998%			---	NV	NV	---	---
Am	---			---	---	NV	NV	99.96%
As	99.999%			LVM	---	NV	---	---
Ba	99.998%			---	---	NV	NV	---
Be	---	---	---	LVM	---	NV	---	99.96%
Bi	---	---	---	---	---	NV	---	99.96%
C14 (organic)	---	---	---	---	Gas	Gas	Gas	0.0%
C14 (in CO3)	---	---	---	---	---	---	---	100.0%
Ca	---	---	---	---	---	NV	---	99.96%
Cd	99.998%	---	---	SVM	SV	SV	SV	---
Ce	---	---	---	---	NV	NV	NV	99.96%
Cl	90.8%	78%	100%	---	SV	Gas	Gas	89.6%
Cm	---	---	---	---	---	NV	NV	99.96%
Co	---	---	---	---	---	NV	---	99.96%
Cr	99.99%	---	---	LVM	---	NV	SV	---
Cs	99.998%	87%	100%	---	SV	SV	SV	95.7%
Eu	---	---	---	---	NV	NV	NV	99.96%
F	84.6%	---	---	---	SV	Gas	---	---
Fe	99.97%	---	---	---	NV	NV	NV	---
Gd	---	---	---	---	NV	NV	NV	99.96%
H3	---	---	---	---	Gas	Gas	Gas	0.0%
Hg	---	---	---	---	SV	Gas	---	0.0%
I	91.9%	75%	100%	---	SV	Gas	Gas	89.0%
Ir	---	---	---	---	---	NV	NV	99.96%
K	99.9%	---	---	---	---	SV	---	---
La	---	---	---	---	NV	NV	NV	99.96%
Li	---	---	---	---	---	SV	---	97.3%
Mg	99.9%	---	---	---	---	NV	---	---
Mn	---	---	---	---	---	NV	---	99.96%
Mo	---	---	---	---	---	NV	SV	97.3%
N	---	---	---	---	---	Gas	---	0.0%
Na	99.995%	---	---	---	---	SV	SV	---
Nb	---	---	---	---	---	NV	NV	99.96%
Nd	---	---	---	---	NV	NV	NV	99.96%
Ni	99.99%	---	---	---	SV	NV	NV	---
Np	---	---	---	---	---	NV	NV	99.96%
P	---	---	---	---	---	SV	---	97.3%
Pa	---	---	---	---	---	NV	NV	99.96%
Pb	99.998%	---	---	SVM	---	NV	SV	---
Pd	---	---	---	---	---	NV	NV	99.96%
Pm	---	---	---	---	NV	NV	NV	99.96%
Pr	---	---	---	---	NV	NV	NV	99.96%
Pu	---	---	---	---	---	NV	NV	99.96%
Rb	---	---	---	---	---	SV	SV	97.3%
Re (Tc surrogate)	99.998%	71%	98%	---	---	---	---	84.5%
Rh	---	---	---	---	---	NV	NV	99.96%
Ru	---	---	---	---	SV	NV	SV	97.3%

Table C-11 FBSR single-pass elemental capture (continued).

Element	Measured capture efficiency, %			EPA HWC MACT definition, Ref. 1	Relative volatility			Estimated or average capture efficiency, %
	Ref. 1	Ref. 2 min	Ref. 2 max		Ref. 3 (for melters)	Ref. 4 (for used fuel separations)	Ref. 5 (for thermal processes)	
S	89.8%	---	---	---	---	SV	---	---
Sb	99.999%	---	---	---	SV	NV	SV	---
Se	99.6%	---	---	---	---	---	SV	---
Si	---	---	---	---	NV	---	---	99.96%
Sm	---	---	---	---	NV	NV	NV	99.96%
Sn	---	---	---	---	---	NV	NV	99.96%
Sr	---	---	---	---	NV	NV	NV	99.96%
Ta	---	---	---	---	---	NV	---	99.96%
Tc	---	80%	86%	---	---	---	---	83.0%
Te	---	---	---	---	SV	---	SV	97.3%
Th	---	---	---	---	---	NV	NV	99.96%
Ti	---	---	---	---	SV	---	SV	97.3%
Tl	99.98%	---	---	---	---	SV	---	---
U	---	---	---	---	---	NV	NV	99.96%
V	---	---	---	---	NV	---	---	99.96%
W	---	---	---	---	NV	---	---	99.96%
Y	---	---	---	---	---	NV	NV	99.96%
Zr	---	---	---	---	NV	NV	NV	99.96%

1. References:

Reference 1. THOR Treatment Technologies, 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.

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2. The estimated capture efficiency was determined for elements which had multiple measured values by (a) calculating the average of those values or by (b) using relative volatility estimates and applying the average measured capture efficiency for non-volatile or semi-volatile elements.

3. Acronyms for metal volatility defined by Environmental Protection Agency (EPA) Hazardous Waste Combustor (HWC) Maximum Achievable Control Technology (MACT) standards: LVM = Low volatility metal (As, Be, Cr); SVM = Semivolatile metal

4. Acronyms for **relative** metals volatility based on vitrification melter tests, used nuclear fuels separations, and other thermal processes: NV = Nonvolatile; SV = Semivolatile; V = Volatile.

5. Calculated average measured Ref. 1 capture efficiency for non-volatile elements: 99.96%

6. Calculated average measured Ref. 1 capture efficiency for semi-volatile elements: 97.3%

[LAW Supplemental Treatment Feed Vector (Case 3335)_with WTP LAW Feed_with Density nrs 27jun18.xlsx]element partition

Mercury is not captured in FBSR product, but quantitatively 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. Figure C-18 shows how the profile of the Hg concentration in the SLAW feed vector decreases by about a factor of 4-10 from the highest initial levels in the first two years. The spent carbon is the permanent disposal path for this Hg.

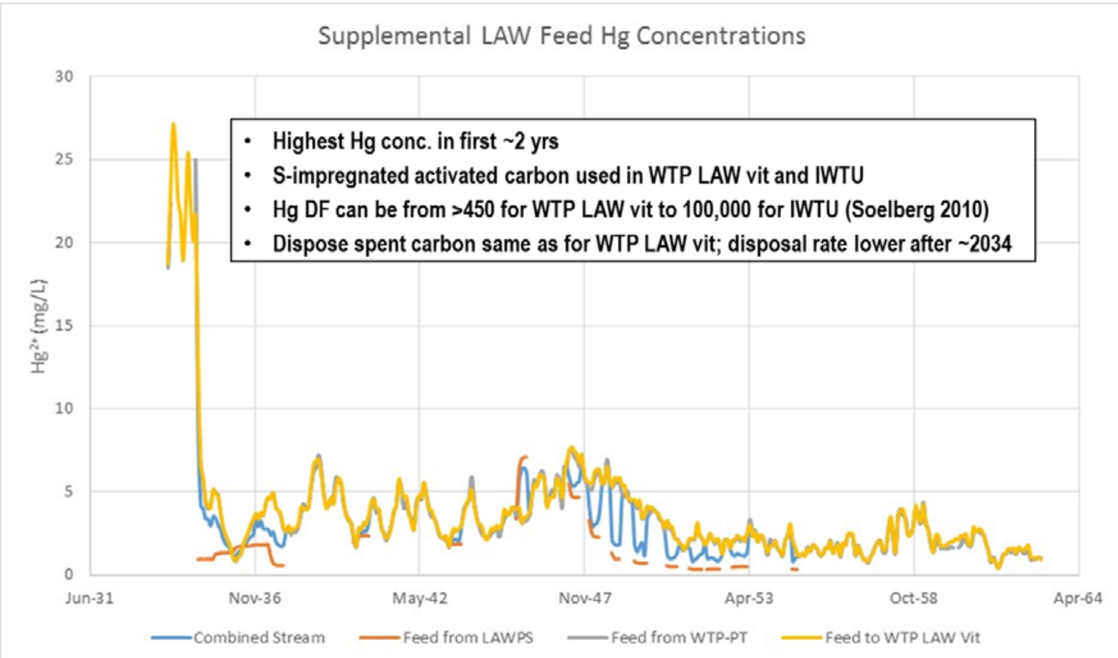


Figure C-18 Control and disposal of Hg in the FBSR process.

As Figure C-19 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) and in spent HEPA filters. Some of the Tc-99 is expected to volatilize and pass into the off-gas system, where it is expected to be captured with sufficiently high efficiency to meet any applicable air emission limits. 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 capture efficiency of about 83-85% in the FBSR product, 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, without needing to take credit for any other disposal pathways such as whatever amounts of Tc-99 adsorb onto the activated carbon for Hg control, or the amount of Tc-99 that might be captured on the spent HEPA filters. Demonstration testing should be done to assess levels of Tc-99 that could occur in the spent carbon and spent HEPA filters.

Figure C-20 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 and in spent HEPA filters. Some of the I-129 is expected to volatilize and pass into the off-gas system, where it is expected to be captured with sufficiently high efficiency to meet any applicable air emission limits. 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, 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, without needing to take credit for any other disposal pathways such as whatever amounts of I-129 adsorb onto the activated carbon for Hg control, or the amount of I-129 that might be captured on the spent HEPA filters. Demonstration testing should be done to assess levels of I-129 that could occur in the spent carbon and spent HEPA filters.

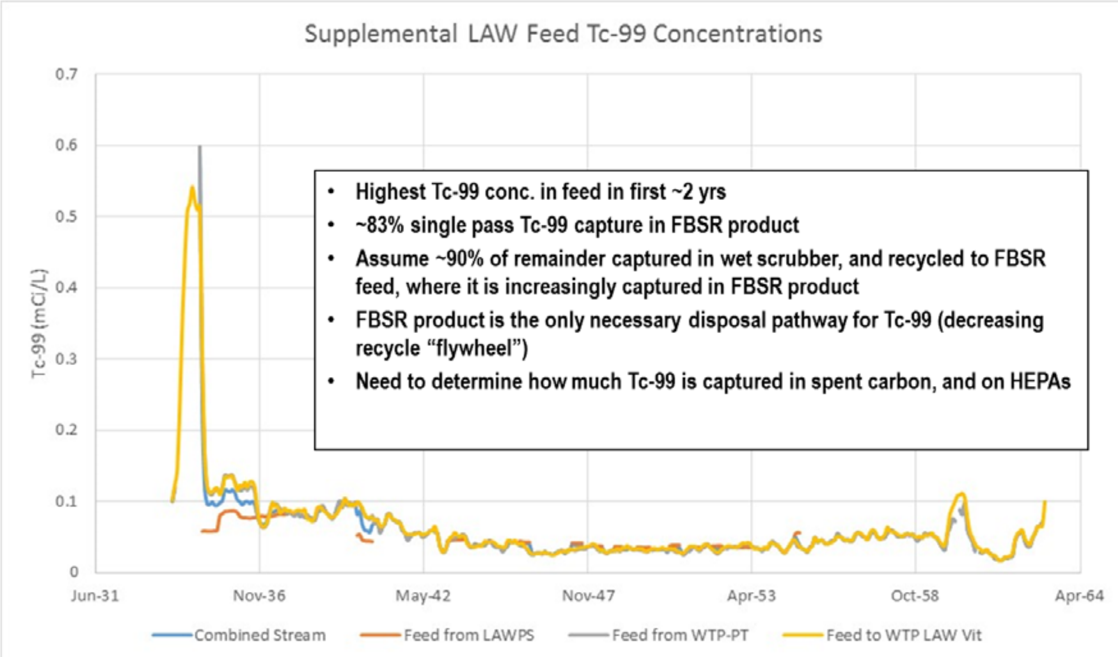


Figure C-19 Control and disposal of Tc-99 in the FBSR process.

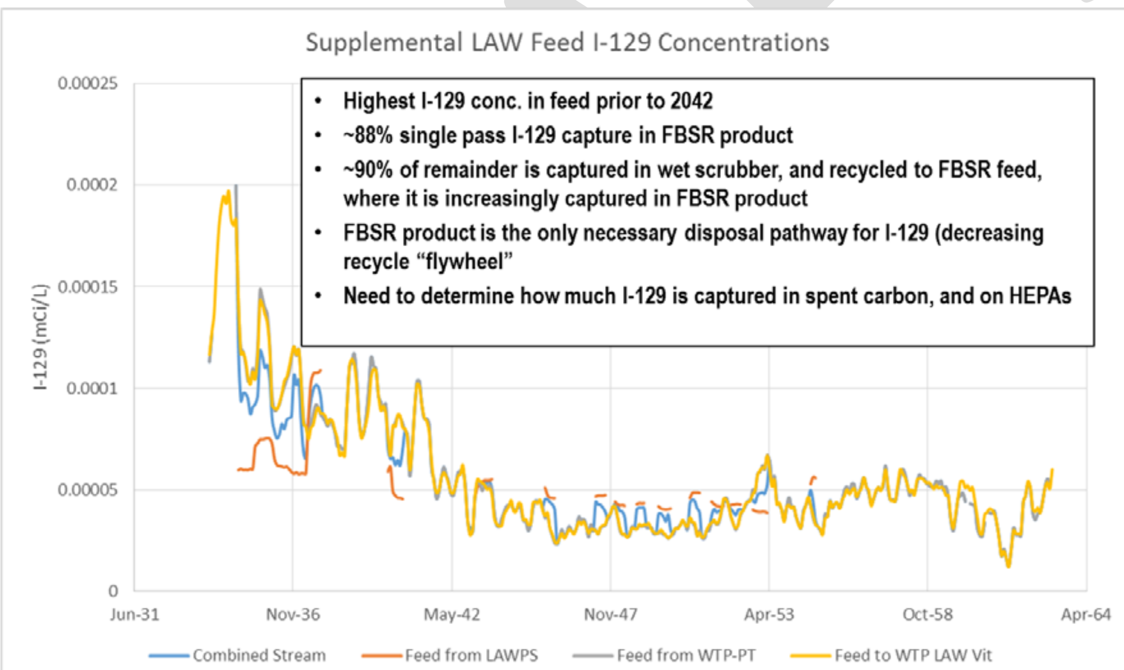


Figure C-20 Control and disposal of I-129 in the FBSR process.

SUMMARY OF IWTU STARTUP CHALLENGES AND RESOLUTIONS

The first-of-a-kind (FOAK) IWTU construction was complete 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-12.

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 / reaction kinetics were not adequately understood.
  - Sufficiency of fluidization was not appropriately assessed.
  - Adequate 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 led to:
  - Various flaws in the design, specifications and operational procedures.
  - 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."

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 IWTU runs with non-radioactive simulant feed planned to be done in 2018. Startup of radioactive SBW treatment operations depend on satisfactory demonstration of the process, equipment, and procedures during non-radioactive operations.

Some challenges remain. Successful operation related to the following issues for long term operation remains to be demonstrated:

Table C-12 IWTU startup challenges and resolutions.

June 2012: Overpressurization of the IWTU system during initial IWTU startup; 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; 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. Coal and charcoal were fed at rates during startup higher than could react with the available oxygen feed. This created more coal and charcoal particles entrained in the process gas stream than could be filtered and removed from the process by the PGF and the Off-gas Filter (OGF, downstream of the Carbon Reduction Reformer [CRR]). This caused filter cake buildup, bridging between filter elements, and 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 emitted from the IWTU stack to the atmosphere. 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. This occurrence had multiple contributing causes including (a) insufficient/immature understanding of how to control the plant and what to expect, (b) inadequate instrumentation, monitoring, and process control strategy, (c) no real-time tracking and assessment of mass & energy balance conditions, (d) many design deficiencies for many facility subsystems and equipment, and (e) inadequate training, oversight, and technical inquisitiveness. The IWTU startup was delayed while changes were determined, tested, and implemented in all of these areas, such as (a) more detailed guidance on the process chemistry and hydrodynamics and better definition of operating limits, (b) implementation of a real-time process control mass/energy balance, (c) additional pressure and pressure drop monitoring, (d) prevention of filter element lifting off of the filter vessel tubesheets, (e) improved filter vessel operation (back-pulsing, hopper level control, and filter dust removal and management), (f) improved solids handling system equipment and operation, and (g) improved startup and operating procedures, control 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 for thousands of hours.
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, where applicable, can be incorporated into the design for SLAW treatment, improving its technical readiness level. • Performance of the solid product handling system: The solid product handling system now operates successfully after modifying solids eductors, operating temperatures and durations, modifying fluidization pads in hoppers, etc. This has been a multiyear improvement process. • Various input gas flowrate measurement and control issues: 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. • DMR and CRR charcoal and coal feed system reliability: The initial performance and reliability has been improved through determination of operating and control parameters, monitoring, maintenance, and changes in the lock-hopper equipment. This is an area of continued monitoring, repairs, and modification when needed. The CRR solid feed systems have been eliminated in the SLAW design.

- DMR product sample collection system operability: DMR product samples are needed to monitor the DMR product particle size and other parameters. This system has been modified several times, resulting in the first successful product sampling in 2017. - PGF filter element breakage: Initially installed sintered metal filter elements cracked and broke due to stress from temperature expansion and contraction within the filter element holders. The holder design and fabrication were changed to eliminate those stresses and improve filter element life. - CRR refractory durability: CRR refractory cracked and spalled due to the frequent temperature cycles during multiple startups. Repairs and modifications have been made to the refractory and heatup-cooldown procedures to improve durability; but 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. - CRR gas injection configuration: Gas injectors were changed to improve stoichiometry for destruction of residual H_2, CO, and hydrocarbons in the DMR outlet gas, and also destruction of residual NO and NO_2, while maintaining the needed temperature and excess oxygen control. This CRR is eliminated in the SLAW design. - In-situ measurement of the CRR outlet oxygen concentration: The O_2 sensors for this harsh, high-temperature measurement were changed due to excessive corrosion and sensor failure. - Carbon bed heatup and temperature control: The heatup and operating procedure and temperature limits were revised to speed heatup and still prevent temperature excursions. - Process and off-gas blower shaft design and performance, and blower control limits: Operation of these blowers, and the shafts, were modified to increase operating life and performance. - HEPA filter element design: 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 current design is working well.
Insufficient DMR bed particle size control from 2016 to present.
Resolutions: The DMR bed particle size distribution results from opposing forces that tend to either grow particles (especially layering of new product onto the surfaces of existing particles) or tend to reduce particle size (through creation of new particles or attrition [break-up] of existing particles), together with periodic removal of bed particles to the product handling system. Many factors affect particle size growth and attrition. Long term operation is needed to achieve particle size control. When needed, alumina seed particles are added. Particle size was not well controlled in IWTU operation prior to 2017. New online Fast Fourier Transform monitoring technology and sampling and analysis continue to be advanced and demonstrated with successive startup runs. IWTU runs planned for 2018 will determine the success of particle size control.
DMR bed "sandcastling" between 2016-2018 to present.
Resolutions: "Sandcastling" occurs when fluidized bed particles, in regions of low fluidizing gas velocity weakly stick together, as the name implies. When this occurs it can grow in size in the vessel, cause fluidizing gas channeling, and reduced mass and heat transfer. Waste feed operations must stop when this occurs, to prevent poor waste feed conversion and bed defluidization. Operation without sandcastling was demonstrated during multiple pilot-scale tests, but it still occurred in full-scale IWTU operation. Several fluidizing gas injection and other modifications have been made to solve this, without success. 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. IWTU runs planned for 2018 will determine the success of these resolutions.
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 over the past three years.

Deposits in and around the auger-grinder plugged the auger-grinder until it was redesigned, tested, and installed, together with improved segregation of moisture and better temperature control low in the DMR. Wall scale formed during operation on in the inside surfaces of the DMR. Modeling and tests indicate that bed fluidization and waste conversion chemistry conditions can cause this wall scale. The modified bed fluidization design, together with chemistry modification through the waste feed additions, and control of particle size, bed temperature, and bed stoichiometry, is expected to provide needed wall scale control. Solid deposits on waste feed injectors can impair 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. IWTU runs planned for 2018 will determine the success of these resolutions.

- Recirculating fluidization caused by having three waste feed nozzles all on one side of the DMR, configured for ease of maintenance instead of for waste feed injection equidistant every 120 degrees around the cylindrical DMR (modeled and mitigated by modifying the fluidizing gas configuration).
- Solids handling systems for the solid granular coal and coke fuels for the DMR and the Carbon Reduction Reformer (CRR), and for the granular product, which are based on mature commercial technology, and much improved during several thousand operating hours since 2012, but still prone to high maintenance.
- The refractory-lined, fluidized bed CRR, which has experienced refractory issues due to the heating-cooling cycles of the process, complicated by the vibration caused by the fluidized bed inside the CRR.
- Prevention of “sandcasting,” and control of wall scale and bed particle size in the DMR have not yet been demonstrated.

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.

TECHNOLOGY READINESS

Technology Readiness Levels (TRLs) for FBSR need to be defined in concert with TRLs for the other technologies so that the same TRL perspective is used for all the technologies. 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.

No formal TRL evaluation has been done for mineralizing FBSR for treating Hanford SLAW. The TRL estimates shown in Figure C-21 for different facility subsystems result from informal and subjective evaluations of this team. Many portions of the steam reforming concept facility such as the waste feed 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. More specifically, these portions of the facility contain mature technologies already demonstrated in the Erwin Resin*Solutions* Facility and in the IWTU. These are rated at TRL 7-9.

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 with TRLs between 4-6 for this particular use for treating Hanford SLAW. While the Erwin Resin*Solutions* Facility has operated at full scale for many years, the low-level waste (LLW) it processes (primarily spent ion exchange resins from U.S. commercial nuclear power plants) is quite different from the Hanford SLAW. While its full scale operation uses equipment and subsystems that can translate to a Hanford SLAW treatment facility, some of these applications are indirect and in many cases not yet fully demonstrated for this application at full scale. And while the Erwin Resin*Solutions* Facility also adds clay to produce a mineralized product, the significant difference in primary waste feeds makes the clay addition methodology much different than the Hanford SLAW concept.

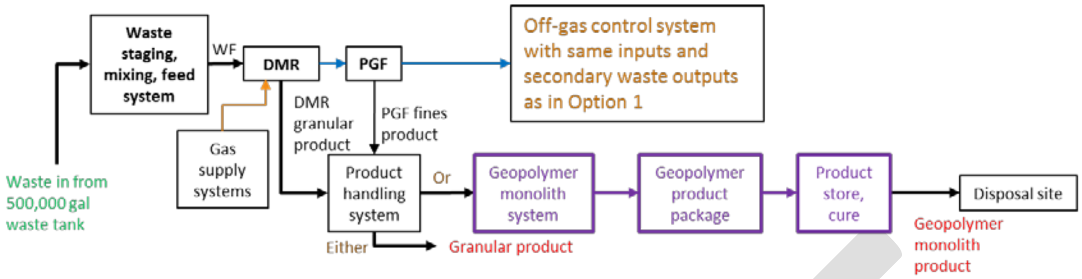
Likewise, the IWTU, while some of its design and operation is even more similar to a Hanford SLAW treatment process, there are important key subsystems that have not yet been proven beyond a pilot-scale level. Indeed, the non-radioactive startup process for the IWTU, which started in about 2012, has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

Many system and subsystem issues with the IWTU have now been solved; startup/commissioning may soon be complete. When complete, this experience will increase the technical maturity of key FBSR components. But some of the design and function of a Hanford SLAW treatment process would by necessity need to be different than in 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.

The IWTU has been described as "first-of-a-kind." 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 TRL 7 and higher 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.



Estimated Technology Readiness Level, assumptions

- Additive, WF systems TRL 7-8
- Gas supply systems TRL 7-9
- Not unique to FBSR, common commercial equipment

- DMR TRL 6
- Unique to FBSR
- Mineralizing flowsheet TRL 6
- Coal feed TRL 7
- Product system TRL 6-7

- Geopolymer monolith system TRL 4-6
- Can use common commercial equipment

- Off-gas system TRL 7-8
- Wet scrubber TRL 4-6
- Not unique to FBSR

- Product cure, store, transport - needs design but TRL 7-8
- Can use common commercial equipment

- Integrated FBSR system TRL is 4-7 because of its dependence on multiple integrated subsystems, until fully integrated pilot and full-scale development and demonstration is achieved for the Hanford SLAW

Figure C-21 Rough maturity level estimates for the FBSR processing system.

SUMMARY

Fluidized bed steam reforming has been researched, demonstrated, and used for treating LLW and mixed LLW for over two decades. Multiple research, development, and demonstration programs have used bench and pilot-scale DMR systems.

Two full scale FBSR facilities include the IWTU for SBW and the Erwin Resin*Solutions* Facility (formerly Studsvik Processing Facility) in Erwin, TN for LLRW and mixed LLW in the US. Studsvik continues to demonstrate FBSR for various customers.

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

- Moderate temperature high enough to destroy organics and NO_x, produce a mineralized durable 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.1.2 Grout

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 treatment and conditioning 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
- Simple and low-cost processing 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
- Suitable for sludge, liquors, emulsified organic liquids and dry solids
- Suitable for a wide range of aqueous compositions
- Good thermal, chemical and physical stability of waste-form
- Alkaline chemistry which ensures low solubility for many key radionuclides
- Non-flammable waste form
- Good waste-form compressive strength which facilitates handling
- Flexible formulation to meet particular waste form requirements
- Processing options are demonstrated for a wide range of waste volumes from > 1.0E+05 L /day (saltstone) to < 0.5 L batches.
- Water in the feed is incorporated into the waste form, minimizing the volume of secondary liquid waste

Grouting technology has been designated as 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 feed solution to 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 where it is 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). The addition of BFS helps to achieve a low activity of oxygen, which maintains some waste constituents (e.g., technetium) in a less-soluble reduced oxidation state.

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 products with favorable properties generally termed cast stone. Lockrem (2005) presents a cast-stone recipe that has favorable properties for Hanford's LAW streams, and it consists of dry blend ingredients in proportions similar to saltstone: 8 wt% OPC, 47 wt% BFS, 45 wt% FA. Other proportions of OPC-BFS-FA have also been investigated (e.g., Lockrem, 2005; Sundaram et al., 2011; Serne et al., 2016).

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 properties of monoliths made from cast stone formulations differ significantly from those made for Hanford low activity waste (LAW) using earlier grout formulations that lacked BFS, particularly with respect to retention of many constituents of 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. As noted, BFS imparts reducing conditions (low oxygen activity) in 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 section 5.3.0.3. 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 waste stream and an improvement in the qualities of the hydrated product such as lower permeability and higher long-term strengths (Wu et al., 1990). A central question remains: How does a grout monolith oxidize under long-term disposal conditions, and how does this impact the long-term retention of redox-sensitive constituents?

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 is 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 blast furnace slag continues to be problematic due to closure and/or idling of blast furnaces and the depletion of old slag piles; yet the demand for BFS may increase in some areas due to projected reductions in the supply of fly ash (USGS, 2017). 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). 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 .

D.1.2.1 Retention Characteristics of Cast Stone
To be written at a later time.

D.2 DESCRIPTION OF FLOWSHEETS

D.2.1 Base Case Scenario

The base-case grout process flow diagram considered in this assessment is shown in Figure D-1, which assumes disposal at the Integrated Disposal Facility (IDF) and no pre-treatment beyond any 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). The base case assumes a semi-continuous batch process.

The choice of this scenario as a base case is not meant to imply that it was considered a viable option. Rather, this particular scenario was chosen as the base case because it is similar to those considered in previous studies (e.g., performance assessments and environmental impact assessments) inasmuch as it does not include any additional pretreatment for radionuclides or organics.

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.

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

Containers are assumed to consist of a heavy duty polypropylene bag lining within an 8.4-m^3 steel box used as a casting frame; this size was chosen to be compliant with disposal at WCS (which is considered in variant 2g2 described in Section A5.3.1.5 below). 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 bagged monoliths are transferred to a lag storage and transport facility prior to shipment to the IDF.

A minimal amount of secondary wastes are anticipated in the base case, 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 base case process is estimated to be medium to high (quantitative range to be determined and provided in later revisions) based on maturity of similar grout-based processes (e.g., SRS saltstone, etc.).

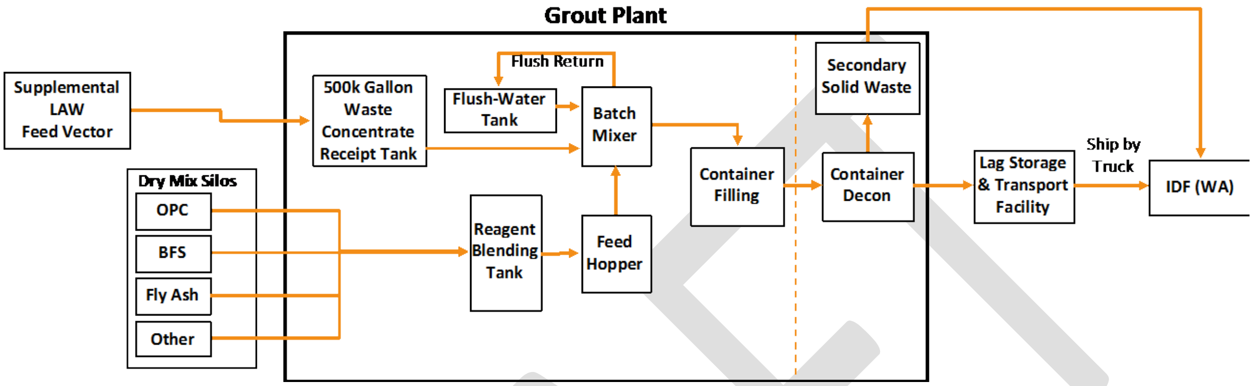

Figure D-1. Process flow diagram for the base-case scenario considered for the grout (cast-stone) process. Base-case scenario assumes no pre-treatment of waste beyond the WTP-PT and LAW-PS as well as disposal at the Integrated Disposal Facility (IDF).

D.2.2 Variant Case with Organics Pretreatment (Variant 2d)

Variant case 2d is similar to the base-case except it includes the addition of pre-treatment for organics and metals as needed to meet land disposal restrictions (LDR) associated with RCRA. The grout process does not inherently destroy organic compounds that may be contained in SLAW, so variant 2d assumes an additional treatment process 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). Various processes are being evaluated in this assessment (see Section XXX). In Figure D-2, this treatment is shown occurring outside the footprint of the grout facility.

The technology readiness level for the variant case 2d is estimated to be medium to high (quantitative range to be determined and provided in later revisions); the incorporation of LDR treatment has minimal impact to the

TRL relative to the base case because organics-treatment is a mature technology and, extensive experience exists with the use of grout to stabilize various LDR metals.

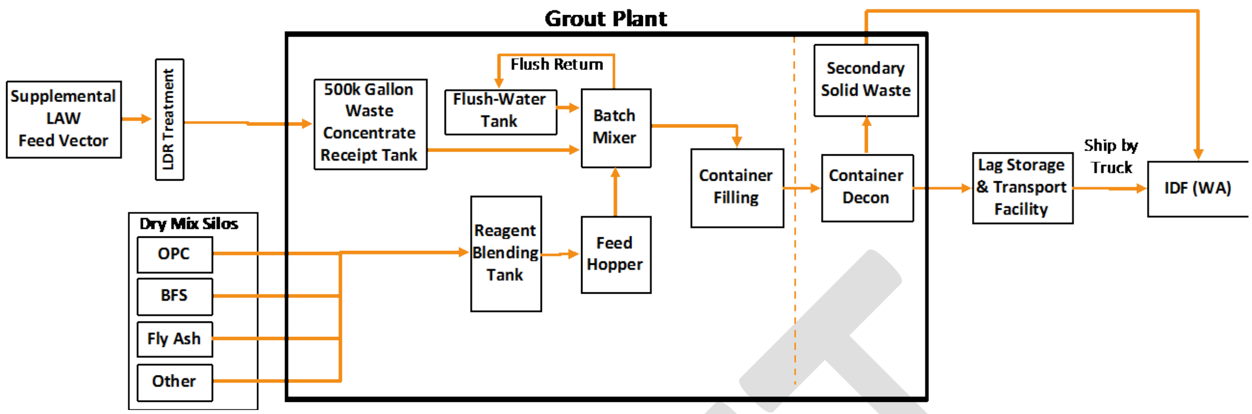

Figure D-2. Process flow diagram for variant case 2d that incorporates a treatment process for organic compounds that may be contained in the SLAW feed (variant 2d).

D.2.3 Variant Cases with Pretreatment for Technetium and Iodine (Variants 2e1 and 2e2)

Two variant cases were considered for the pretreatment of technetium (Tc) and iodine (I); both variant cases are otherwise similar to the base-case. As noted, new cast-stone grout formulations have been developed and tested to reduce the release of technetium and iodine, and other technologies (e.g., getters added to the SLAW feed) have also shown promise. However, variant cases 2e1 and 2e2 recognize the potential need to remove these constituents prior to forming the grout monoliths.

Various processes are being evaluated in this assessment (see Section XXX). These processes are assumed to occur in a facility prior to SLAW feed being delivered to the grout facility, so they are shown generically outside of the grout-plant footprint.

The assessment considered two scenarios for the disposition of the removed Tc/I. In Figure D-3a (variant 2e1), the removed Tc/I are transferred to the high-level vitrification facility, where they can be incorporated into the HLVIT process. In Figure D-3b (variant 2e2), the removed Tc/I are disposed of at the WCS facility in Texas; this disposal may require additional handling components (e.g., grouting), which are not shown (see Section XXX for details).

The technology readiness levels for the variant cases 2e1 and 2e2 are estimated to be low (quantitative range to be determined and provided in later revisions) based on the separation challenges and the need to scale-up processes.

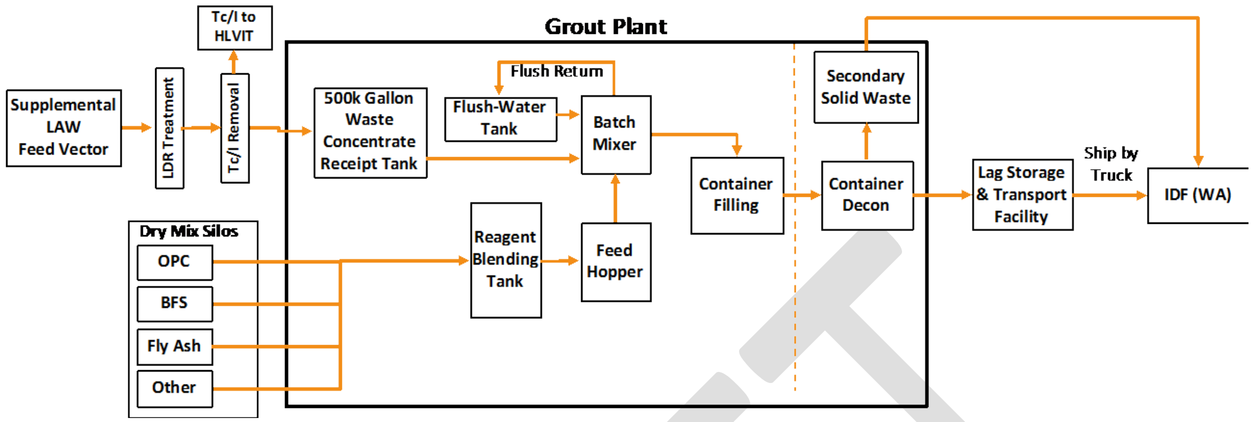

Figure D-3a. Process flow diagram for variant case 2e1 that incorporates a pretreatment process for technetium and iodine, which are transferred to the high-level vitrification facility.

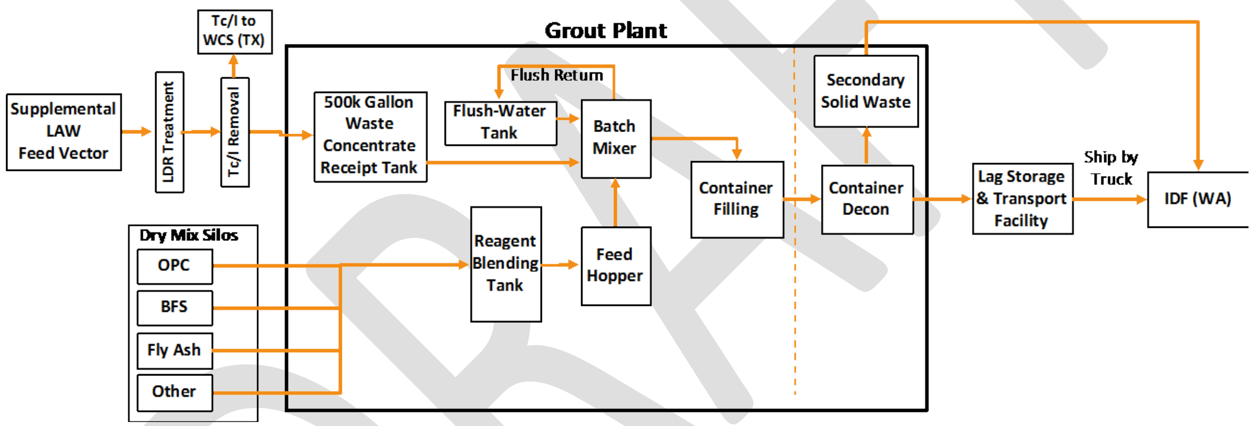

Figure D-3b. Process flow diagram for variant case 2e2 that incorporates a pretreatment process for technetium and iodine, which are then disposed of at the WCS facility in Texas.

D.2.4 Variant Case with Storage at the WCS Facility (Variant 2g2)

One variant case was considered for the storage of the grouted monoliths at the Waste Control Specialists (WCS) facility in Texas, which can store and dispose Class A, B and C low-level radioactive waste, hazardous waste, and byproduct materials. Figure D-4 shows the associated process flow diagram. Waste must still comply with RCRA requirements, so this variant assumes treatment of LDR organics and metals as needed. Solid secondary wastes for this variant are assumed to be disposed of at the IDF.

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, as noted below in Section xx, strontium removal could be considered as part of this variant as a potentially significant cost-savings measure.

The technology readiness level for the variant case 2g2 is estimated to be medium to high (quantitative range to be determined and provided in later revisions); the incorporation of LDR treatment has minimal impact to the

TRL relative to the base case because organics-treatment is a mature technology and, extensive experience exists with the use of grout to stabilize various LDR metals; similarly the shipping and disposal at WCS does not significantly impact the TRL estimated for the base case.

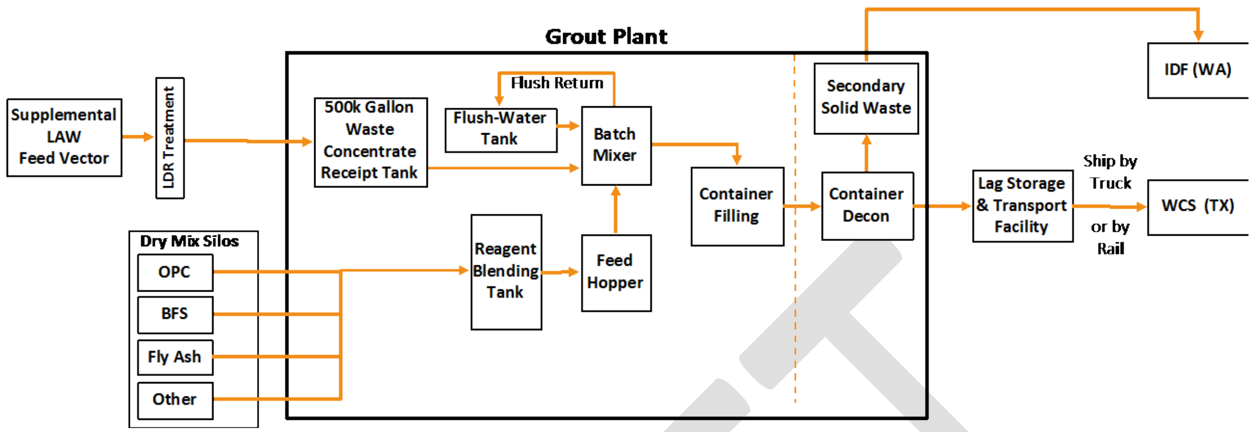

Figure D-4. Process flow diagram for variant case 2g2 that incorporates a pretreatment process for technetium and iodine, which are then disposed of at the WCS facility in Texas.

D.2.5 Variant Case with Pretreatment for Strontium (Variant 2f)

An additional variant case was considered for shipment to the WCS facility in Texas, incorporating the pretreatment of strontium (Sr). The process is otherwise similar to the variant case 2g2.

Removal of soluble strontium could be considered to as a cost-saving measure by addressing waste classification. 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 strontium-removal processes are being evaluated in this assessment (see Section XXX). These processes are assumed to occur in a facility prior to SLAW feed being delivered to the grout facility, so they are shown generically outside of the grout-plant footprint.

Figure D-5 (variant 2f) shows the strontium removal process with the removed strontium being transferred to the high-level vitrification facility, where it can be incorporated into the HLVIT process.

The technology readiness level for the variant case 2f is estimated to be medium to high (quantitative range to be determined and provided in later revisions); the incorporation of Sr treatment has minimal impact to the TRL relative to variant 2g2 (Section D.2.4).

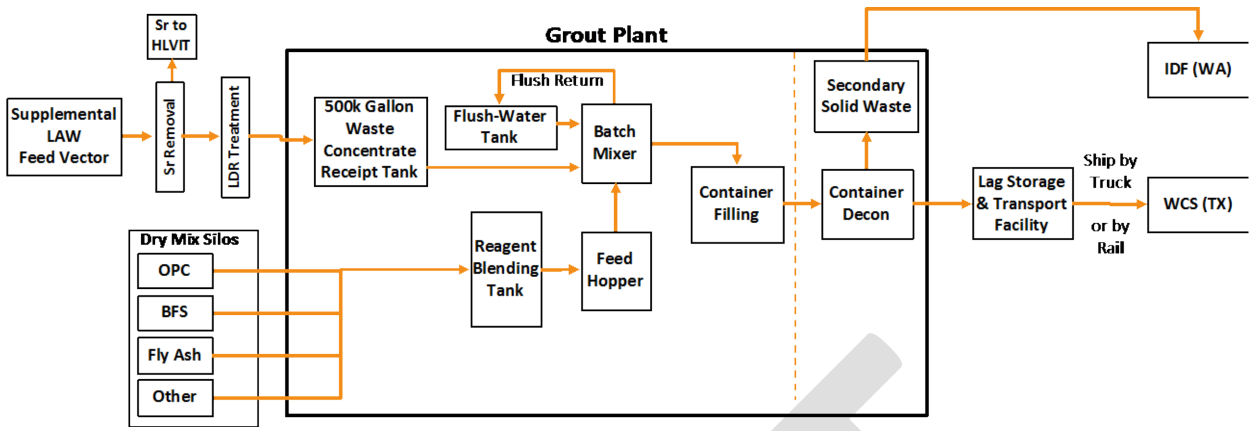

Figure D-5. Process flow diagram for variant case 2f that incorporates a pretreatment process for strontium, which is then transferred to the high-level vitrification facility.

D.2.6 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.

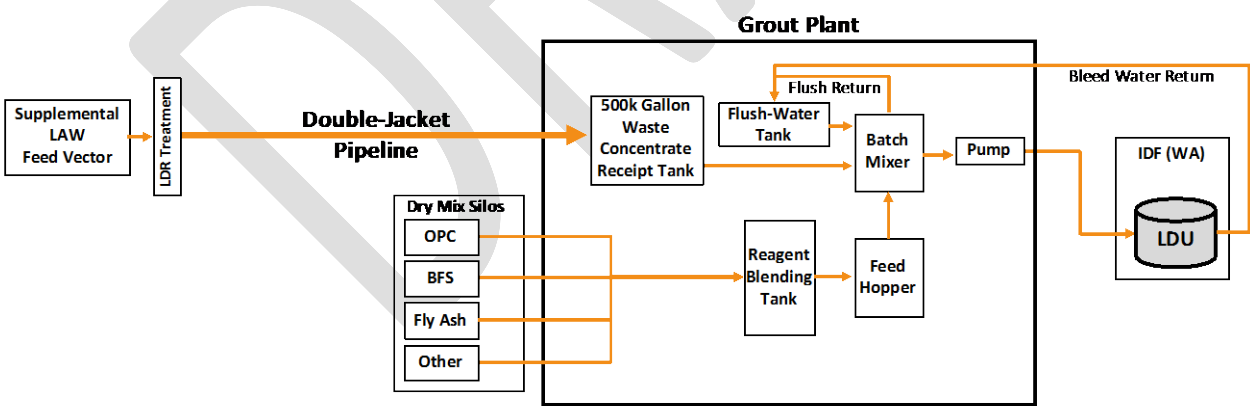

Figure D-6. Process flow diagram for the direct pumping of grout into large disposal units (LDU) in the IDF.

D.3 ASSUMPTIONS
To be written at a later time.

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. 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 goalsA demonstrated performance for a grouted waste form that is comparable to that for glass (which is permitted for disposal in the IDF);
- The use of the WCS facility in Texas for the disposition of the grouted SLAW waste form;
- The removal (by pre-treatment) of radionuclides of 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.

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. 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, as considered in Sections A5.3.1.2 and A5.3.1.5.

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 either 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) or hydrated lime (e.g., Um et al., 2016). 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, including for example stockpiling of materials with appropriate properties. In addition, research on substitute materials could be considered as an anticipatory measure for blast furnace slag and fly ash
- Construction and start-up testing of a facility will not be met within budget or timeline. This risk was evaluated to be low due to extensive experience constructing similar facilities (i.e., DOE's grouting experience) and based on it being a simple facility/process (ambient temperature, minimal offgas, commercially available reagents)
- Inability to mature a specific aspect of the process to a high TRL within time. This risk is most applicable to new formulations such as the use of getters for Tc and I. This risk was evaluated to be low due to relatively simple modifications needed to incorporate new formulations into the process and due to the existing body of testing on various formulations

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

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

D.4.4 Additional Potential Risks Applicable to Specific Grout Processes Considered

Base Case—Primary potential risks associated with the base case process (A5.3.1.1) include failure to achieve waste acceptance, the presence of LDR organics, and the failure of a specific monolith to meet waste specifications (e.g., failure of TCLP for LDR metals, failure to set, etc.).

Variant 2d—Changes in primary potential risks associated with the variant case 2d (A5.3.1.2) relative to the base case include removing risk associated with the presence of LDR organics but adding risk associated with the potential impact of the organics-treatment process on waste form performance (e.g., increased mobility of redox-active metals).

Variant 2e1—Changes in primary potential risks associated with the variant case 2e1 (A5.3.1.3) relative to the base case include reducing the risk of failing to achieve waste form acceptance at IDF by eliminating LDR organics and Tc/I. This option may include an additional risk associated with the inability to send Tc/I to the high level vitrification facility.

Variant 2e2—Changes in primary potential risks associated with the variant case 2e1 (A5.3.1.3) relative to the base case include reducing the risk of failing to achieve waste form acceptance at IDF by eliminating LDR organics and Tc/I. This option may also mediate the additional risk for variant 2e1 associated with the inability to send Tc/I to the high level vitrification facility.

Variant 2g2—Changes in primary potential risks associated with the variant case 2g2 (A5.3.1.4) relative to the base case include reducing the risk of failing to achieve waste form acceptance at IDF by shipping the primary waste to the WCS facility (which can accept Tc/I). This option could include an additional risk associated with waste form acceptance should the WCS option change in the future.

Variant 2f—Changes in primary potential risks associated with the variant case 2f (A5.3.1.5) relative to the base case are those listed for variant 2g2.

Opportunity to Store Waste in Large Disposal Unit—Changes in primary potential risks associated with the opportunity to pump the grout into large disposal units in the IDF relative to the base case include reducing the risk of failing waste form performance criteria (a larger sized waste form is projected to perform better than smaller sized waste forms in the context of radionuclide release). However, this option includes additional risk associated with permitting of a large disposal unit in the IDF.

D.5 BENEFITS AND COST ESTIMATE
To be written at a later time.

D.6 SCHEDULE

To be written at a later time.

D.7 REGULATORY COMPLIANCE

To be written at a later time.

D.8 OBSTACLES

To be written at a later time.

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APPENDIX E. EXPANDED DISCUSSION – OTHER APPROACHES

TBD

APPENDIX F. EXPANDED DISCUSSION: COMPARATIVE ANALYSIS OF APPROACHES

F.1 SUMMARY

The Analytical Hierarchy Process (AHP) decision-making tool was used to evaluate approaches for treatment of supplemental low-activity waste (LAW) at the Hanford Nuclear Reservation. The AHP was developed at the Wharton School of Business to assist in making complex decisions with multiple, often conflicting, criteria for the US Arms Control and Disarmament Agency. It has been widely used in business, government, research and development, defense, and other domains involving decisions in which choice, prioritization or forecasting is needed.

Twenty-two potential approaches were identified by the team, and twelve options were fully evaluated and ranked as shown in Table F-1. They are listed in rank order from higher (green) to lower (red) overall scores. Ten of the options were not fully evaluated because the team felt that they were bounded by the cases listed in Table F-1.

Table F-1. Ranking of Approaches for Supplemental Treatment of Low-Activity Waste

Options Evaluated	Score (1 – 100)
2g2 - Grout with LDR pretreatment; Primary to WCS	87
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	85
3b - Steam reforming to WCS, Secondary to WCS	77
1c - Vit to IDF, Secondary to WCS	67
2d - Grout with LDR pretreatment, Primary & secondary to IDF	67
2 - Grout - Base Case	65
1g - Bulk vit in large container to IDF, Secondary to WCS	63
2e2 - Grout with LDR and Tc & I pretreatment to WCS, Primary & secondary to IDF	63
2e1 - Grout with LDR and Tc & I pretreatment to HLVit, Primary & secondary to IDF	62
1 - Vitrification - Base Case	56
1d - Bulk vitrification	55
3 - Steam reforming - Base Case	53

Higher Lower

The options of pretreating secondary LAW and grouting for disposal at WCS received the higher overall scores, followed by steam reforming for disposal at WCS. Vitrification, bulk vitrification, and steam reforming for disposal at IDF received the lower scores. Grouting (with or without pretreatment) for disposal at IDF and bulk vitrification for disposal at IDF ranked in the middle.

F-2 EVALUATION METHODOLOGY

The options analysis was performed using the 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.[69]

The 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. The pairwise comparison tables are provided in the Tables F-11 and F-12, and the weighted selection criteria and metrics are summarized in Table F-2.

Five ratings were used to determine how well an option satisfies a particular metric: 5-Strong, 4-Moderate/Strong, 3-Moderate, 2-Low, 1-None. Definitions were developed by the team for the ratings for each metric. The criteria and metrics definitions are given in the Table F-13.

Each option was assigned a rating between 1 and 5 for each metric. The ratings were made by the 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 from Table F-2. An overall score for an option was obtained by summing the weighted ratings. The highest possible score that can be obtained through this process is 100.

[69] Thomas L. Saaty, "A Scaling Method for Priorities in Hierarchical Structures," *Journal of Mathematical Psychology*, 15: 234–281, 1977.

Table F-2. Criteria and Metrics Weighting Factors

Criteria	Criteria Weighting (%)	Metrics	Metric Weighting (%)	Relative Weight of Metric (%)
Technical Maturity and Process Simplicity and Reliability	—	TRL	7.6	0.45
		Maturation of TRL	33.6	1.97
		Number of unit operations	13.7	0.80
		Simplicity of feed start-up/shutdown	22.3	1.31
		Simplicity of control of unit operations	22.8	1.34
Safety	—	Nuclear and radiological hazards	41.5	2.07
		Chemical hazards	23.2	1.16
		Physical hazards	12.0	0.60
		Transportation hazards	23.2	1.16
Operational Flexibility	—	Ability to handle range of feed vector compositions	31.5	2.63
		Ability to handle range of feed vector flowrates	19.3	1.61
		Ability to prevent/rework off-spec product	38.8	3.23
		Analytical requirements	10.4	0.87
Economy	12.0	Development cost	10.1	1.22
		Capital cost (includes permits, deactivation and decommissioning etc.)	54.0	6.51
		Operational / annual cost	35.9	4.32
Schedule (Speed)	11.4	Development time prior to design	20.0	2.28
		Time to complete design, construction, and hot start-up	80.0	9.11
Imperviousness to Risks	7.6	Project risks	33.3	2.52
		Operational execution risks	19.0	1.44
		TRL-related risks	47.6	3.61
Primary Waste Form Compliance	19.0	Primary waste form compliance	100.0	18.96

Secondary Waste	11.4	Quantity	25.0	2.85
		Compatible with existing/draft disposal site waste acceptance criteria	75.0	8.54
Regulatory Considerations	15.9	Permitting/licensing complexity for new facilities and processes	31.3	4.99
		Compliance with shipping regulations	11.3	1.81
		Permitting/licensing complexity for disposal	57.4	9.14
End State Decommissioning	3.5	Complexity (includes residual inventory)	75.2	2.65
		Waste volume	24.8	0.87

F.3 OPTIONS EVALUATION: GO/NO GO SCREENING

Twenty-two options, summarized in Table F-3 and described in more detail in the TableF-14, were identified by the team for consideration in the evaluation process. Each potential option was reviewed to determine whether it should be evaluated in detail. The evaluation team determined that 10 of the approaches would be adequately bound by the approaches that were evaluated and rated. Vitrification with disposal at IDF is the present plan of record and was carried forward as a baseline for comparison.

Table F-3. Approaches Considered for Evaluation

Option Title	**Category of Option**	**Evaluated?**
1 - Vitrification - Base Case	Base	Yes
1a - Vit to WCS, Secondary to IDF	Variant	No
1b - Vit to WCS, Secondary to WCS	Variant	No
1c - Vit to IDF, Secondary to WCS	Variant	Yes
1d - Bulk Vitrification	Variant	Yes
1e - Bulk vit to WSC, Secondary to IDF	Variant	No
1f - Bulk vit to WSC, Secondary to WCS	Variant	No
1g - Bulk vit in large container to IDF, Secondary to WCS	Variant	Yes
2 - Grout - Base Case	Base	Yes
2a - Grout to WCS, Secondary to IDF	Variant	No
2b - Grout to WCS, Secondary to WCS	Variant	No
2c- Gout to IDF, Secondary to WCS	Variant	No
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	Variant	Yes
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	Variant	Yes
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	Variant	Yes
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	Variant	Yes
2g1 - Grout with LDR pretreatment, Primary to WCS – B-25 box	Variant	No
2g2 - Grout with LDR pretreatment; Primary to WCS – 8.4m^3 bag in box	Variant	Yes
3 - Steam Reforming - Base Case	Base	Yes
3a - Steam Reforming to WCS, Secondary to IDF	Variant	No
3b - Steam Reforming to WCS, Secondary to WCS	Variant	Yes
3c - Steam Reforming to IDF, Secondary to WCS	Variant	No

F.4 EVALUATION OF OPTIONS

The 12 approaches identified for evaluation were assessed using the AHP methodology. Each option was assigned a rating between 1 and 5 (See Table F-15) for each metric by the 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 from Table F-2. An overall score for an option was obtained by summing the weighted ratings. The relative rankings are summarized in Table F-4 from higher (green) to lower (red) overall total project scores. Table F-4 also shows the scores for each option using equal weighting factors for the 10 criteria (i.e., 10% each). Table F-5 shows the team scores for each option at the criterion level.

Table F-4. Relative Comparison of Options Using Group Weighting and Equal Weighting Factors

Options Evaluated	Group Weighting Score (1 – 100)	Equal Weighting Score (1 – 100)
2g2 - Grout with LDR pretreatment; Primary to WCS	87	83
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	85	78
3b - Steam Reforming to WCS, Secondary to WCS	77	73
1c - Vit to IDF, Secondary to WCS	67	59
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	67	75
2 - Grout - Base Case	65	76
1g - Bulk vit in large container to IDF, Secondary to WCS	63	60
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	63	66
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	62	66
1 - Vitrification - Base Case	56	53
1d - Bulk Vitrification	55	56
3 - Steam Reforming - Base Case	53	60

Higher Lower

Table F-5. Relative Comparison of Options on a Criterion-by-Criterion Basis

Options	Technical Maturity and Process Simplicity & Reliability	Safety	Operational Flexibility	Economy	Schedule ("Speed")	Imperviousness to Risks	Primary Waste Form Compliance	Secondary Waste	Regulatory Considerations	End State Decommissioning
Relative Weight	5.9	5	8.3	12	11.4	7.6	19	11.4	15.9	3.5
2g2 - Grout with LDR pretreatment; Primary to WCS	5	2	7	8	8	7	19	11	15	4
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	4	2	7	9	8	6	19	11	15	4
3b - Steam Reforming to WCS, Secondary to WCS	4	3	8	6	5	6	19	11	15	2
1c - Vit to IDF, Secondary to WCS	3	2	7	2	5	5	19	9	16	0
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	5	4	7	11	8	6	0	11	10	4
2 - Grout - Base Case	6	4	6	12	9	6	0	11	8	4
1g - Bulk vit in large container to IDF, Secondary to WCS	4	2	8	4	6	4	9	9	15	2
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	4	3	7	10	8	5	0	11	12	3
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	4	4	7	10	8	5	0	11	12	3
1 - Vitrification - Base Case	3	3	7	2	5	5	19	2	11	0
1d - Bulk Vitrification	4	3	8	4	6	4	9	4	10	2
3 - Steam Reforming - Base Case	4	4	8	7	5	6	0	9	10	2

Higher Lower

Major observations from the options analysis include:

- Using the team's criteria weighting factors shown in Table F-2, the options of pretreating secondary LAW (for LDR and/or Sr), and grouting for disposal at WCS received the higher overall scores. Steam reforming for disposal at WCS received the next highest score. Vitrification, bulk vitrification, and steam reforming for disposal at IDF received the lower scores. Grouting (with or without pretreatment) and bulk vitrification for disposal at IDF ranked in the middle.

- When the 10 weighting factors were assigned equal weighs (10% each), the relative ranking of the options did not change significantly. The options of pretreating secondary LAW (for LDR and/or Sr) and grouting for disposal at WCS still received the higher overall scores. Grouting for disposal at IDF (with and without LDR pretreatment) moved up in the ranking. Steam reforming for disposal at IDF moved from a lower score to an “in between” middle range score. Vitrification and bulk vitrification for disposal at IDF remained the lower scored options.
- Individual criterion scores in Table F-5 indicate that the higher overall rated options (pretreating secondary LAW for LDR and/or Sr for disposal at WCS) received high ratings in all categories except safety and operational flexibility. The lower overall rated options (vitrification, bulk vitrification, and steam reforming for disposal at IDF) tended to receive high ratings in these categories and low ratings in the other criterion categories.

F.5 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to understand the impacts of the weighting factors on the various evaluation criteria. Five different criteria weighting factor schemes were evaluated for comparison to the team-generated weighting factors shown in Table F-4. 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. The results are shown in Tables F-6 through F-10.

Table F-6. Comparison of Options with 30% Weighting on Criteria Named in Column and Residual Equally Divided Across Other Criteria

Options	Technical Maturity and Process Simplicity & Reliability	Safety	Operational Flexibility	Economy	Schedule ("Speed")	Imperviousness to Risks	Primary Waste Form Compliance	Secondary Waste	Regulatory Considerations	End State Decommissioning
2g2 - Grout with LDR pretreatment; Primary to WCS	87	77	86	82	82	88	89	89	87	89
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	80	74	83	81	79	80	86	84	84	86
3b - Steam Reforming to WCS, Secondary to WCS	70	70	76	67	66	74	78	77	77	67
1c - Vit to IDF, Secondary to WCS	55	56	63	49	54	60	67	61	67	45
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	80	76	79	81	75	79	60	82	74	82
2 - Grout - Base Case	81	79	75	81	76	77	59	81	70	81
1g - Bulk vit in large container to IDF, Secondary to WCS	64	60	70	57	60	61	60	65	69	60
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	68	68	72	71	69	69	53	74	70	70
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	67	69	72	70	68	67	53	74	70	70
1 - Vitrification - Base Case	49	51	56	43	48	53	61	43	54	39
1d - Bulk Vitrification	59	56	65	52	55	57	55	52	58	55
3 - Steam Reforming - Base Case	60	62	66	59	56	62	46	63	60	57

Table F-7. Comparison of Options with 40% Weighting on Criteria Named in Column and Residual Equally Divided Across Other Criteria

Options	Technical Maturity and Process Simplicity & Reliability	Safety	Operational Flexibility	Economy	Schedule ("Speed")	Imperviousness to Risks	Primary Waste Form Compliance	Secondary Waste	Regulatory Considerations	End State Decommissioning
2g2 - Grout with LDR pretreatment; Primary to WCS	88	73	86	80	80	89	90	90	88	90
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	79	71	84	80	78	80	88	86	85	88
3b - Steam Reforming to WCS, Secondary to WCS	69	68	78	65	63	74	82	79	79	65
1c - Vit to IDF, Secondary to WCS	53	55	65	45	52	61	72	63	72	38
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	82	75	80	83	74	80	51	84	72	84
2 - Grout - Base Case	83	80	75	83	76	78	51	84	67	84
1g - Bulk vit in large container to IDF, Secondary to WCS	65	58	73	54	58	61	58	67	72	58
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	67	68	74	72	69	69	46	77	71	71
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	67	69	74	72	69	66	45	77	71	70
1 - Vitrification - Base Case	48	52	60	39	46	55	66	39	57	33
1d - Bulk Vitrification	61	56	69	50	54	57	54	50	59	54

Table F-8. Comparison of Options with 50% Weighting on Criteria Named in Column and Residual Equally Divided Across Other Criteria

Options	Technical Maturity and Process Simplicity & Reliability	Safety	Operational Flexibility	Economy	Schedule ("Speed")	Imperviousness to Risks	Primary Waste Form Compliance	Secondary Waste	Regulatory Considerations	End State Decommissioning
2g2 - Grout with LDR pretreatment; Primary to WCS	89	69	86	78	79	90	92	92	88	92
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	78	67	84	80	77	79	90	87	86	90
3b - Steam Reforming to WCS, Secondary to WCS	68	67	80	62	60	75	85	82	81	62
1c - Vit to IDF, Secondary to WCS	52	54	68	40	50	62	76	65	76	32
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	84	75	82	85	74	81	43	87	71	87
2 - Grout - Base Case	86	81	74	86	76	78	42	87	64	87
1g - Bulk vit in large container to IDF, Secondary to WCS	65	57	77	51	57	60	57	68	76	57
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	67	67	76	73	69	70	38	80	73	71
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	67	70	76	73	69	66	38	79	72	71
1 - Vitrification - Base Case	48	52	63	36	45	57	72	36	59	28
1d - Bulk Vitrification	62	56	73	48	54	57	54	48	60	54
3 - Steam Reforming - Base Case	61	65	73	59	53	66	33	66	61	55

Table F-9. Comparison of Options with 60% Weighting on Criteria Named in Column and Residual Equally Divided Across Other Criteria

Options	Technical Maturity and Process Simplicity & Reliability	Safety	Operational Flexibility	Economy	Schedule ("Speed")	Imperviousness to Risks	Primary Waste Form Compliance	Secondary Waste	Regulatory Considerations	End State Decommissioning
2g2 - Grout with LDR pretreatment; Primary to WCS	90	65	87	76	77	91	94	94	89	94
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	77	63	85	79	75	78	92	88	88	92
3b - Steam Reforming to WCS, Secondary to WCS	67	66	82	60	57	76	88	84	83	60
1c - Vit to IDF, Secondary to WCS	51	53	70	36	48	63	81	67	81	26
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	86	74	83	87	73	82	34	90	69	90
2 - Grout - Base Case	88	83	74	88	75	79	34	89	61	89
1g - Bulk vit in large container to IDF, Secondary to WCS	66	56	80	48	56	60	56	69	79	56
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	66	67	78	74	69	70	30	82	74	72
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	66	70	78	74	69	65	30	82	73	72
1 - Vitrification - Base Case	47	53	66	33	44	59	78	32	62	22
1d - Bulk Vitrification	63	56	78	45	53	57	53	46	60	53
3 - Steam Reforming - Base Case	62	66	76	59	51	67	26	68	62	54

Table F-10. Comparison of Options with 70% Weighting on Criteria Named in Column and Residual Equally Divided Across Other Criteria

Options	Technical Maturity and Process Simplicity & Reliability	Safety	Operational Flexibility	Economy	Schedule ("Speed")	Imperviousness to Risks	Primary Waste Form Compliance	Secondary Waste	Regulatory Considerations	End State Decommissioning
2g2 - Grout with LDR pretreatment; Primary to WCS	90	61	87	74	75	92	95	95	90	95
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	76	60	86	79	74	77	94	90	89	94
3b - Steam Reforming to WCS, Secondary to WCS	66	64	84	57	54	76	91	87	86	57
1c - Vit to IDF, Secondary to WCS	49	53	72	32	46	64	86	69	86	19
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	87	74	84	89	72	83	26	92	68	92
2 - Grout - Base Case	91	84	73	90	75	79	25	92	58	92
1g - Bulk vit in large container to IDF, Secondary to WCS	67	54	84	45	54	59	54	71	82	54
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	66	67	80	75	69	70	23	85	75	73
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	66	71	79	75	69	65	23	85	75	73
1 - Vitrification - Base Case	47	54	70	29	43	61	83	29	64	17
1d - Bulk Vitrification	65	56	82	43	52	57	52	44	61	52
3 - Steam Reforming - Base Case	62	68	80	59	50	69	20	70	62	53

The sensitivity analysis indicates that the options had essentially the same relative rankings as those in Table F-4 when the weightings of the criteria were each changed to 30%. Table F-6 indicates that at 30% weightings the higher overall rated options (pretreating secondary LAW for LDR and/or Sr for and grouting for disposal at WCS) received high ratings in all categories. The lower overall rated options (vitrification, bulk vitrification, and steam reforming for disposal at IDF) received the lower ratings in all categories. At the 30% weightings, grouting and grouting with LDR pretreatment for disposal at IDF also scored high in most but not all criterion categories.

As the criterion weighting factors were increased from 30% to 70% as shown in Tables F-6 through F-10, the options to pretreat secondary LAW for LDR and/or Sr and grout for disposal at WCS began to rate lower on safety due to open road transfer of large volumes of waste, and grouting with or without LDR treatment began to rate higher in most categories except primary waste form compliance. The lower overall rated options (vitrification, bulk vitrification, and steam reforming for disposal at IDF) tended to receive the lower ratings in all criterion categories for all weighting factors ranging from 30 to 70%.

Table F-11 Pairwise Evaluation of Selection Criteria

Criteria 1	Very Strong (4	Strong (3X)	Moderate (2X)	Equal	Moderate (2X)	Strong (3X)	Very Strong (4	Criteria 2
Technical Maturity and Process Simplicity & Reliability			x					Safety
Technical Maturity and Process Simplicity & Reliability					x			Operational Flexibility
Technical Maturity and Process Simplicity & Reliability						x		Economy
Technical Maturity and Process Simplicity & Reliability						x		Schedule ("Speed")
Technical Maturity and Process Simplicity & Reliability					x			Imperviousness to Risks
Technical Maturity and Process Simplicity & Reliability							x	Primary Waste Form Compliance
Technical Maturity and Process Simplicity & Reliability					x			Secondary Waste
Technical Maturity and Process Simplicity & Reliability						x		Regulatory Considerations
Technical Maturity and Process Simplicity & Reliability			x					End State Decommissioning

Table F-12. Pairwise Evaluation of Selection Metrics

Metric Table #1	**Technical Maturity and Process Simplicity & Reliability**							
Metric 1								***Metric 2***
TRL						x		Maturation of TRL
TRL					x			Number of unit operations
TRL						x		Simplicity of Feed Start-up/shut down
TRL						x		Simplicity of control of unit operations
Maturation of TRL			x					Number of unit operations
Maturation of TRL		x						Simplicity of Feed Start-up/shut down
Maturation of TRL			x					Simplicity of control of unit operations
Number of unit operations					x			Simplicity of Feed Start-up/shut down
Number of unit operations					x			Simplicity of control of unit operations
Simplicity of Feed Start-up/shut down				x				Simplicity of control of unit operations
Metric Table #2	**Safety**							
Metric 1								***Metric 2***
Nuclear and Radiological Hazards			x					Chemical Hazards
Nuclear and Radiological Hazards		x						Physical Hazards
Nuclear and Radiological Hazards			x					Transportation Hazards
Chemical Hazards			x					Physical Hazards
Chemical Hazards				x				Transportation Hazards
Physical Hazards					x			Transportation Hazards
Metric Table #3	**Operational Flexibility**							
Metric 1								***Metric 2***
Ability to handle range of feed vector compositions			x					Ability to handle range of feed vector flowrates
Ability to handle range of feed vector compositions					x			Ability to prevent/rework off-spec product
Ability to handle range of feed vector compositions		x						Analytical requirements
Ability to handle range of feed vector flowrates					x			Ability to prevent/rework off-spec product
Ability to handle range of feed vector flowrates			x					Analytical requirements
Ability to prevent/rework off-spec product		x						Analytical requirements
Ability to prevent/rework off-spec product								
Analytical requirements								
Metric Table #4	**Economy**							
Metric 1								***Metric 2***
Development Cost							x	Capital Cost (includes permits & D&D etc.)
Development Cost							x	Operational / Annual Costs
Capital Cost (includes permits & D&D etc.)		x						Operational / Annual Costs
Metric Table #5	**Schedule ("Speed")**							
Metric 1								***Metric 2***
Development time prior to design							x	Time to complete design, construction, and hot startup
Metric Table #6	**Imperviousness to Risks**							
Metric 1								***Metric 2***
Project risks			x					Operational Execution Risks
Project risks					x			TRL related risks
Operational Execution Risks					x			TRL related risks
Metric Table #7	**Primary Waste Form Compliance**							
Metric 1								***Metric 2***
Metric Table #8	**Secondary Waste**							
Metric 1								***Metric 2***
Quantity						x		Compatible with Existing / Draft Disposal Site WAC
Metric Table #9	**Regulatory Considerations**							
Metric 1								***Metric 2***
Permitting / licensing complexity for new facilities & processes		x						Compliance with shipping regulations
Permitting / licensing complexity for new facilities & processes						x		Permitting / licensing complexity for disposal of primary & secondary waste
Compliance with shipping regulations							x	Permitting / licensing complexity for disposal of primary & secondary waste
Metric Table #10	**End State Decommissioning**							
Metric 1								***Metric 2***
Complexity (includes residual inventory)		x						Waste Volume

Table F-13. Definitions for Rating Options

Criteria	Metric	Metric Definition	Metric Bin Descriptions		
			5 - Strongly	**3 - Moderate**	**1 - None**
Technical Maturity and Process Simplicity & Reliability	**TRL**	Assessment of the TRL levels for all unit operations based on EM TRL Guide	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	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	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	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	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**	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	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	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	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**	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	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	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	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 F-13. Definitions for Rating Options Continued

Criteria	Metric	Metric Definition	Metric Bin Descriptions		
			5 - Strongly	3 - Moderate	1 - None
Economy	**Development Cost**	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.)	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	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**	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	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
Imperviousness to Risks	**Project risks**	Resilience to impacts from outside factors such as funding availability, support facilities, etc.	Risks low compared to other options	Risks moderate compared to other options	Risks high compared to other options
	Operational Execution Risks	Resilience to impacts during operations by changes in items such as feed vector variability, changes in disposal WAC, raw materials, etc.	Risks low compared to other options	Risks moderate compared to other options	Risks high compared to other options
	TRL related risks	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
Waste Form Performance	**Compatible with Disposal Site WAC**	Confidence that process can produce waste form that can meet WAC and performance requirements	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 F-13. Definitions for Rating Options Continued

Criteria	Metric	Metric Definition	Metric Bin Descriptions		
			5 - Strongly	3 - Moderate	1 - None
Secondary Waste	**Quantity**	Volume of secondary waste produced	Low relative to other alternatives	Moderate relative to other alternatives	High relative to other alternatives
	Compatible with Disposal Site WAC	Confidence that process can produce waste form that can meet WAC and performance requirements	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**	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	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	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)**	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	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

Table F-14. Description of Treatment Options Evaluated

Option Title	Attributes	Assumptions	Pathways	Category of Option
1 - Vitrification - Base Case	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	Base
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	Base Vit case with primary to IDF, secondary to WCS		Variant
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/EFF	Variant
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;		Variant
2 - Grout - Base Case	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	Base
2d - Grout with LDR pretreatment, Primary & Secondary waste to IDF	Primary Waste Disposition: IDF 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, Primary to IDF, Secondary to IDF		Variant

Table F-14. Description of Treatment Options Evaluated Continued

Option Title	Attributes	Assumptions	Pathways	Category of Option
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		Variant
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		Variant
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		Variant
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		Variant
3 - Steam Reforming - Base Case	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)	Base
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		Variant

Table F-15. Team Scores of Options

Criteria	Technical Maturity and Process Simplicity & Reliability					Safety				Operational Flexibility				Economy		
Metrics	TRL	Maturation of TRL	Number of unit operations	Simplicity of Feed Start-up/shut down	Simplicity of control of unit operations	Nuclear and Radiological Hazards	Chemical Hazards	Physical Hazards	Transportation Hazards	Ability to handle range of feed vector compositions	Ability to handle range of feed vector flowrates	Ability to prevent/rework off-spec product	Analytical requirements	Development Cost	Capital Cost (includes permits & D&D etc.)	Operational / Annual Costs
Options																
1 - Vitrification - Base Case	4	5	1	1	2	3	2	3	5	5	3	5	1	5	1	2
1c - Vit to IDF, Secondary to WCS	4	5	1	1	2	3	2	3	4	5	3	5	1	5	1	2
1d - Bulk Vitrification	3	5	2	4	3	3	2	3	5	5	5	5	3	3	2	3
1g - Bulk vit in large container to IDF, Secondary to WCS	3	5	2	4	3	3	2	3	4	5	5	5	3	3	2	3
2 - Grout - Base Case	4	5	5	5	5	5	4	3	5	3	5	4	4	4	5	5
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	3	5	4	5	5	4	3	3	5	5	5	4	4	3	5	5
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	2	3	3	5	4	4	3	3	5	5	5	4	3	2	4	5
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	2	3	3	5	4	4	3	3	4	5	5	4	3	2	4	5
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	2	4	3	5	4	4	3	3	1	5	5	4	4	3	5	3
2g2 - Grout with LDR pretreatment; Primary to WCS	3	5	4	5	5	4	3	3	1	5	5	4	4	3	5	2
3 - Steam Reforming - Base Case	3	5	2	3	3	4	3	3	5	5	5	4	5	3	3	4
3b - Steam Reforming to WCS, Secondary to WCS	3	5	2	3	3	4	3	3	3	5	5	4	5	3	3	3

Table F-15. Team Scores of Options Continued

Criteria	Schedule ("Speed")		Imperviousness to Risks			Primary Waste Form Compliance	Secondary Waste		Regulatory Considerations			End State Decommissioning	
Metrics	Development time prior to design	Time to complete design, construction, and hot startup	Project risks	Operational Execution Risks	TRL related risks	Compatible with Existing / Draft Disposal Site WAC	Quantity	Compatible with Existing / Draft Disposal Site WAC	Permitting / licensing complexity for new facilities & processes	Compliance with shipping regulations	Permitting / licensing complexity for disposal of primary & secondary waste	Complexity (includes residual inventory)	Waste Volume
Options													
1 - Vitrification - Base Case	5	2	1	5	5	5	1	2	5	5	3	1	1
1c - Vit to IDF, Secondary to WCS	5	2	1	5	5	5	1	5	5	5	5	1	1
1d - Bulk Vitrification	3	3	1	3	5	3	1	3	4	5	3	3	3
1g - Bulk vit in large container to IDF, Secondary to WCS	3	3	1	3	5	3	1	5	4	5	5	3	3
2 - Grout - Base Case	4	4	5	1	5	1	5	5	4	5	2	5	5
2d - Grout with LDR pretreatment, Primary & Secondary to IDF	3	4	5	2	5	1	5	5	4	5	3	5	5
2e1 - Grout with LDR and Tc & I Pretreatment to HLVit, Primary & Secondary to IDF	3	4	4	4	3	1	4	5	4	5	4	4	4
2e2 - Grout with LDR and Tc & I Pretreatment to WCS, Primary & Secondary to IDF	3	4	5	4	3	1	4	5	4	5	4	4	4
2f - Grout with LDR and Sr pretreatment to HLVit, Primary to WCS	3	4	4	4	4	5	4	5	4	5	5	5	5
2g2 - Grout with LDR pretreatment; Primary to WCS	3	4	5	4	5	5	5	5	4	5	5	5	5
3 - Steam Reforming - Base Case	2	3	3	3	5	1	4	4	4	5	3	3	3
3b - Steam Reforming to WCS, Secondary to WCS	2	3	3	4	5	5	4	5	4	5	5	3	3

APPENDIX G. EXPANDED DISCUSSION: COST ESTIMATE METHODOLOGY AND BASIS

G.1 SUMMARY

This document lays out preliminary capital and life-cycle costs for the base case 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.

G.2 ESTIMATE PURPOSE

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 treatment options.

Class 5 estimates have the least project definition available (from 0% to 2%) and therefore have very wide accuracy 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 project team Subject Matter Experts (SME) 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.

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 purpose, scope and assumptions of the planning estimate provided.

G.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, truckand 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.
- 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.

G.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.

G.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.

G.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.

G.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.

G.5.3 Fluid 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.

G.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 – but account for the consistency of design and engineering support.

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. This limited number of individual estimates, but does not reflect the range expected for the various technologies. 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 project team SMEs 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 shipmen, 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.

A. 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. See Table G-1, Vitrification Base Scope.

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. See Table G-2, Vitrification Variant 1.

B. 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. See Table G-3, Grout Base Scope

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. See Table G-4, Grout Variant 1

Another variant evaluated was construction of the grout plant at IDF. See Table G-5, Grout Variant 2.

Opportunities with type of shipping packaging and shipping options to final storage locations exist.

C. 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 1.5M 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. See Table G-6, Fluid Bed Steam Reforming Base Scope.

High scope for this process assumes a grout plant is required for each DMR unit to form a monolithic product. See Table G-7, Fluid Bed Steam Reforming Base Variant.

G.7 WORK BREAKDOWN STRUCTURE

Development.
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 technology base operations and designated variants.

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.

Table G-1 – Vitrification Base Scope

	Technology Development	TEC/OPC	Life Cycle – Operations	D&D
Low Range	$340M	$6800M / $800M	$10,000M	$330M

High Range	$440M	$8800M / $1040M	$13,000M	$430M

Table G-2 – Vitrification Variant 1

	Technology Development	TEC/OPC	Life Cycle – Operations	D&D
Low Range	$680M	$6800M / $560M	$8500M	$330M
High Range	$880M	$8800M / $730M	$11,000M	$430

Table G-3 – Grout Base Scope

	Technology Development	TEC/OPC	Life Cycle – Operations	D&D
Low Range	$90M	$300M / $200M	$1100M	$25M
High Range	$120M	$390M / $260M	$1400M	$35M

Table G-4 – Grout Variant 1

	Technology Development	TEC/OPC	Life Cycle – Operations	D&D
Low Range	$120M	$400M / $250M	$1200M	$35M
High Range	$160M	$520M / $320M	$1600	$40M

Table G-5 – Grout Variant 2

	Technology Development	TEC/OPC	Life Cycle – Operations	D&D
Low Range	$75M	$250M / $200M	$1000M	$25M
High Range	$100M	$320M / $260M	$1300M	$30M

TableG- 6 – Fluid Bed Steam Reforming Base Scope

	Technology Development	TEC/OPC	Life Cycle – Operations	D&D
Low Range	$480M	$1600M / $300M	$2500M	$95M
High Range	$620M	$2100M / $390M	$3300M	$120M

Table G-7 – Fluid Bed Steam Reforming Variant 1

	Technology Development	TEC/OPC	Life Cycle – Operations	D&D
Low Range	$520M	$1800M / $400M	$3300M	$110M
High Range	$680M	$2300M / $520M	$4300M	$140M

G.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.

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 H. EXPANDED DISCUSSION – DISPOSAL SITE CONSIDERATIONS

H.1 INTRODUCTION

This chapter 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 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 facility licensed by the State of Texas.

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 accomodate wastes with higher concentrations of I-129 and Tc-99 while meeting performance objectives, but no off-site shipping is required.

This Section begins with a description of the key assumptions used in the analysis, and is followed by a review of the characteristics of the SLAW waste forms (WFs) requiring disposal. The remainder of this section is divided into two large subsections, one subsection addressing disposal at the IDF and one subsection addressing disposal at the WCS facility in west Texas. The general layout of each subsection is similar, beginning with a description of the facility, followed by a review of key regulatory requirements, the waste acceptance criteria (WAC), the classification of the wastes for disposal using the WAC, and finally, cost considerations. A simple schematic of the overarching activities is presented in Figure H-1.

H.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 permit, licenses and costs.

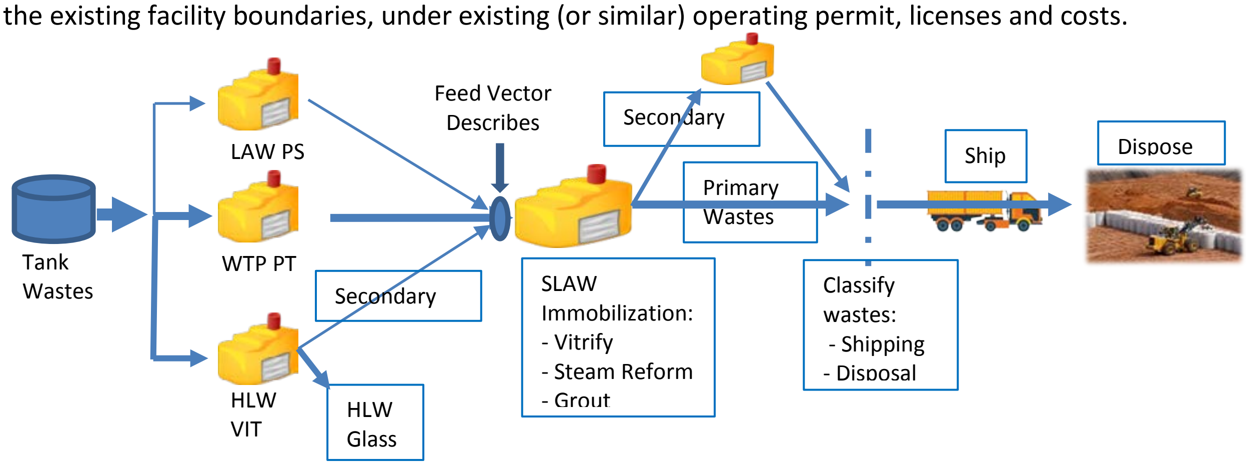

Figure H-1 Simple Schematic of Overarching Activities

H.3 WASTE FORM CHARACTERISTICS

H.3.1 Characteristics of Waste to be Immobilized

The characteristics of the SLAW that will be immobilized are described by the SLAW Supplemental Treatment Feed Vector (or simply the Feed Vector), which is discussed in detail in Section 2.3.

The SLAW wastes are derived from tank wastes that have been pretreated in one of two pretreatment facilities, the WTP PT and the LAW PS, and the SLAW also includes certain nuclides captured as secondary wastes during the verification of the HLW fraction. The SLAW is baselined to be produced from January of 2034 through February of 2063; a 29-year period. However, the production of significant volumes of SLAW do not begin until January 2035; a 28-year period. In summary, the Feed Vector provides data for 29 years, but volumes necessary for immobilization are generated over a 28-year period.

The Feed Vector provides very detailed, projected information on the characteristics of the SLAW, which is important, as the Feed Vector describes the input to the immobilization facility for vitrification, steam reforming and grouting. The information in the Feed Vector includes:

- The <u>monthly volume</u> of SLAW produced by pretreatment in the WTP PT and in the LAW PS, and
- The <u>specific activity of 47 nuclides</u> in from each waste stream, for each month.

The Feed Vector also provides useful summary statistics, including:

- The average specific activity of each of the 47 nuclides across the 29 years
- The highest and lowest specific activity of each nuclide across the 29 years, and
- The highest volume of SLAW produced in one month and the lowest volume in one month.

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.

Table H-1 provides summary statistics for the SLAW that will be immobilized and disposed; a total of 54,000,000 gallons (at 264.2 gallons/m3 = 204,400 m3). Table H-2 provides an example of a fraction of the information available in the Feed Vector for a specific month. Table H-2 presents the radiological content of SLAW from the WPT PT for April 2060. The month of April 2060 was picked as the example because zero volume of SLAW is produced the month earlier (in March 2060) and the row of values for April 2060 was easy to read, being below a vacant row.

Table H 1 Summary Statistics for the SLAW to be Treated and Disposed

Total volume of SLAW to be immobilized Jan 2034 – Feb 2063 (349 months)	54 Mgal (**204,400 m3**)
Maximum volume in one month (WTP PT + LAW PS)	3700 kgal (14,000 m3) March 2040
Average monthly volume (= total volume/337 months) Note: Jan 2035 is the first month with significant volume, so 337 months of immobilization, not 349	160 kgal (**606.5 m3**)

Table H-2 Example: Radiological Content of SLAW from WPT PT for April 2016

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			

The volume of SLAW produced in April 2060 is anticipated to be 7.56 kgal (28.6 m3); a low volume month, as compared to the projected monthly average of 110 kgal (416 m3) for the WTP PT. Even though April 2060 is a low volume month, the specific activity of two important nuclides (I-129 and Tc-99) is very similar to the average concentrations. For I-129, the specific activity (4.3 E-5 Ci/m3) is similar to the average activity for the 29 years (5.5 E-5Ci/m3), and the specific activity of Tc-99 in April 2060 (8.0 E-2 Ci/m3) also similar to the average specific activity of 5.6 E-2 Ci/m3.

H.3.1.1 Characteristics of the Primary Waste Forms

The detailed characteristics of the primary WFs can be derived from information found in the Feed Vector and the knowledge of three parameters:

1. How much primary WF is produced from each unit of pretreated input (e.g., for grouting, 1 liter of pretreated SLAW input (described by the Feed Vector) will produce 1.8 liters of grout WF)
2. The density of the primary WF
3. Nuclides in the pretreated SLAW input that are transferred to a secondary waste stream during the treatment process (e.g., the high temperatures of vitrification may transfer some of the volatile I-129 to a secondary WF; these “scrubber liquid wastes” are described below).

Later in this report, the characteristics of the primary WFs will be combined with Feed Vector data, to determine the classification of the final WF for off-site transport and disposal.

H.3.1.2 Secondary Waste Forms

In addition to the primary WFs, three categories of secondary waste forms may be produced.

In all cases, the immobilization processes will generate <u>secondary solid wastes</u> (SSWs). These SSWs might include: HEPA air filters, personal protective equipment, contaminated equipment and lab wipes. The <u>SSWs</u> will be grouted prior to disposal.

In three variant cases, specific nuclides will be removed from the feed stream prior to immobilization. The three variants that will generate pretreatment wastes (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, 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 and disposed at WCS.

Finally, the high temperatures of vitrification may transfer a portion of the volatile nuclides to the scrubber liquid wastes (SLW).

H.3.1.3 Characteristics of Vitrified Waste Form and Secondary Wastes for Disposal

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 H-3 and H-4.

Table H-3 Characteristics of the Vitrified Waste Form - Canister

Volume change caused by vitrification	
Density of final WF	
Secondary solid wastes	Yes, always
Pretreatment wastes	No cases
Scrubber liquid wastes	yes, how much Tc-99 and I-129 to secondary??
Total volume (204,400 m3 x 1.2)	245,300 m3
Average volume / month (w/337 months)	m3 / month

Table H-4 Characteristics of the Vitrified Waste Form - Bulk

Volume change caused by steam reforming	
Density of final WF	
Secondary solid wastes	Yes, always
Pretreatment wastes	No cases
Scrubber liquid wastes	yes, how much Tc-99 and I-129 to secondary??
Total volume (204,400 m3 x xx)	m3
Average volume / month (w/337 months)	m3 / month

H.3.1.4 Characteristics of Steam Reformed Waste Form and Secondary Wastes for Disposal

Steam reforming and the steam reformed 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 H-5

H.3.1.5 Characteristics of Grout Waste Form and Secondary Wastes for Disposal

Grouting and the grouted WF 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 H-6

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.

Table H-5 Characteristics of Steam Reformed Waste Form - Granular

Volume change caused by steam reforming	1.2 (increases volume & decreases specific activities)
Density of final WF	800 kg/m3 (50 lb/ft3)
Secondary solid wastes	Yes, always
Pretreatment wastes	No cases
Scrubber liquid wastes	No cases
Total volume (204,400 m3 x 1.2)	245,300 m3
Average volume (total/337 months)	728 m3 / month

Table H-6 Characteristics of Grouted Waste Form

Volume change caused by grouting	1.8 (increases volume & decreases specific activities)
Density of final WF	1770 kg/m3 (110 lb/ft3) (0.0624 lb./ft per kg/m3)
Secondary solid wastes	Yes, always
Pretreatment wastes	Yes, for 2e1, 2e2 and 2f
Scrubber liquid wastes	No cases
Total volume (204,400 m3 x 1.8)	367,900 m3
Average volume (total/337 months)	1092 m3 / month

H.4 INTEGRATED DISPOSAL FACILITY

H.4.1 General Description

The primary purpose for the Hanford Integrated Disposal Facility (IDF) is to provide for disposal of immobilized low-activity waste (ILAW) from the Waste Treatment Plant (WTP) and future supplemental LAW facility, solid mixed waste from WTP and SLAW operations, solidified waste from treatment of WTP and SLAW secondary liquid effluents, spent and failed LAW melters from the WTP, and incidental waste that results from the operation of IDF. The IDF was constructed in 2006. It consists of two segregated, separate cells: Cell 1 is for radioactive mixed low-level waste (MLLW) that contains dangerous or hazardous waste and is regulated under RCRA (See Ref. 1); Cell 2 is for radioactive only low-level waste that is regulated by DOE. Cell 1 is permitted by Ecology and is identified as Unit 11, under the Hanford Site Wide RCRA Permit, Cell 2 is regulated under DOE O 435.1.

The IDF is an expandable landfill located in the 200 East Area of the Hanford Site. The IDF is 223 m by 233 m by 14 m deep. At this initial size, it has a disposal capacity is 82,000 m3. At full build out, the facility will measure approximately 446 m by 555 m by 14 m deep, providing a disposal capacity of about 900,000 m3. Cells 1 and 2 will be approximately equal sized. The IDF is a double-lined landfill that has a leachate collection and removal system that have secondary containment and leak detection systems. The Leachate Collection System is designed to segregate leachate collected from the individual cells. A high point down the center of the liner system ensures the leachate from the RCRA permitted cell does not contaminate the leachate from the non-RCRA cell. The IDF includes a secondary leak detection system (SLDS), the purpose of which is to provide access to the area immediately below the Leak Detection System (LDS) sump area. Both the RCRA and non-RCRA permitted cells of the IDF have a 90-day accumulation area for collection of leachate in a large tank for the Leachate Collection and Removal System and the LDS, and a smaller portable container for the SLDS. The tanks have secondary containment. Leak detection of the tanks is provided by monitoring of the secondary containment. The leachate is to be sampled before transfer to Hanford's Liquid Effluent Retention Facility/Effluent Treatment Facility (LERF/ETF) for treatment.

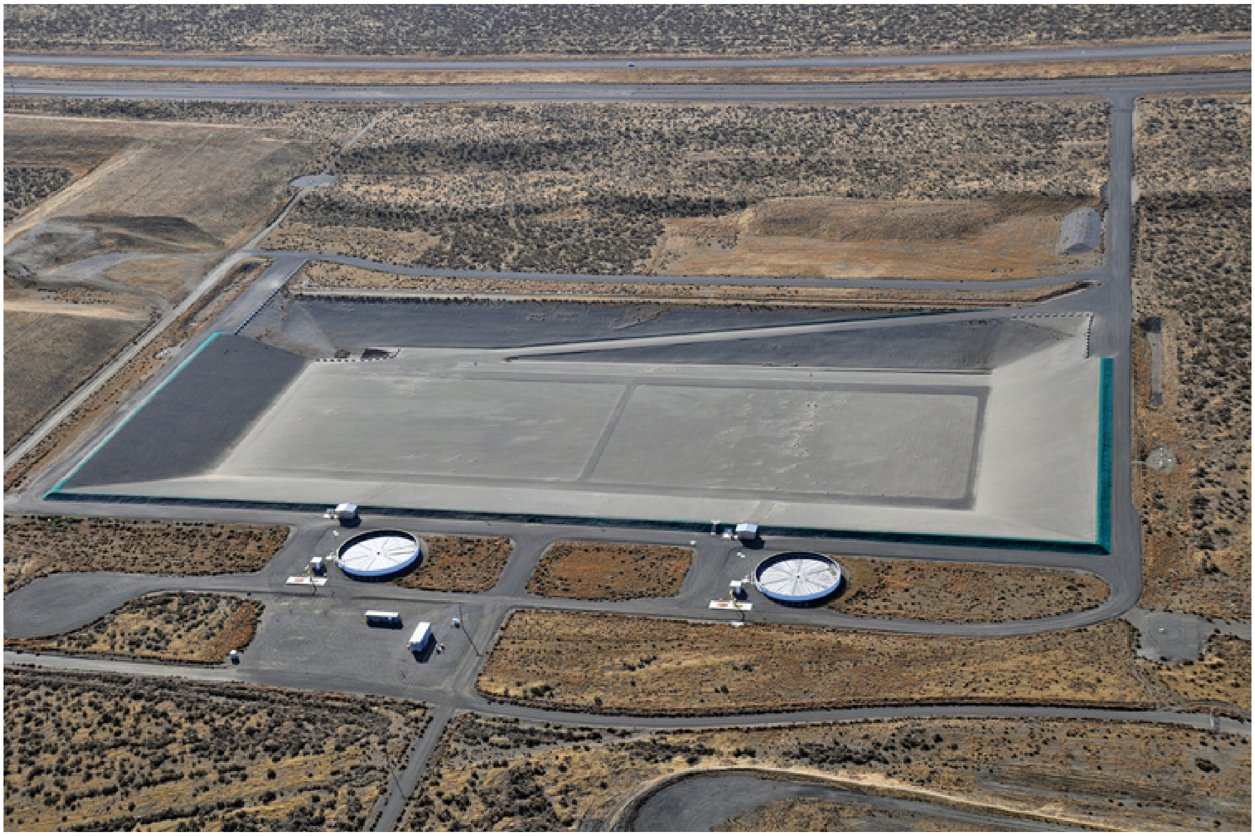

Figure H-2. Aerial View of IDF in the Hanford Site 200-East Area Southwest of WTP.

H.4.2 Key Regulatory Requirements

For purposes of this analysis, only disposal in the RCRA permitted portion of the IDF is considered. A DOE O 435.1 performance assessment (PA) has been developed and is undergoing review by the U.S. Nuclear Regulatory Commission (NRC)[70]. The DOE and Ecology agreed that they would complete one PA 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, that is incorporated by reference into WAC 173-303-140. To date, IDF has not received any dangerous waste. The facility is in a "pre-active life" status. There are several IDF permit conditions that need to be met before the facility can begin to accept waste.

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. The DOE and its contractors completed a waste incidental to reprocessing (WIR), which documents that the DOE has satisfied all treatment requirements to determine that the waste is LAW and thus suitable for near-surface disposal. Per DOE O 435.1, DOE Headquarters must issue a Disposal Authorization (DA) statement which authorizes the IDF to begin accepting waste, assuming the balance of the RCRA permit conditions have been satisfied.

[70] P. Lee. 2018. "Overview of the 2017 IDF Performance Assessment for LAW." Presented at the National Academy of Sciences Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation public meeting, February 28, 2018. TOC-PRES-18-0441-VA. Washington River Protection Solutions. Richland, Washington.

H.4.3 Waste Acceptance Criteria

Ecology recently finalized the WAC for the IDF Permit (Ref. 1). In the WAC, the generator of a waste or waste stream is responsible for developing and providing characterization information and waste profiles (e.g., descriptions, analytical data for constituents and constituent concentrations, and quantities of waste), and a waste designation (determination as to whether a waste is regulated as a hazardous or dangerous substance) for each waste source. Waste profiles must be provided and approved by IDF prior to any waste shipment to ensure compliance with the IDF WAC. Washington State LDR requirements are found in WAC 173-303-140 (See Ref. 2), and Federal treatment standards are contained in 40 CFR 268.4, Subpart D. The WAC for dangerous waste and radionuclides also evolves from the IDF PA.

Other waste acceptance criteria for the IDF include:

- Wastes must be 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 Perma-Fix, or other 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

H.4.4 Classification of Waste Forms for Disposal

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H.4.5 Hosts Considerations for Disposal

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H.4.6 Summary for IDF

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H.5 WASTE CONTROL SPECIALISTS

H.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 of land that is 35 miles west of Andrews, Texas and 5 miles 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 casks.

They have three separate disposal facilities for radioactive wastes, including (1) a facility for "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 11.e(2) byproduct material, and (3) the Federal Waste Disposal Facility (FWF). Figure H-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, for wastes from the DOE and other federal agencies.

H.5.1.1 Site Characteristics

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 sample, 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.[71]

H.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. The multi-barrier cap will be a minimum of 25 feet (~8 m) thick and will be completed at-grade. Class B and C LLW and MLLW are disposed in Modular Concrete Canisters (MCCs), which are 6-inch (150-mm) thick, steel reinforced concrete containers. The combined characteristics (no drinking water aquifer, thick red clay beds, 2-m (7 ft) -thick multi-barrier liner and MCCs) give WCS the most robust design of any Agreement State licensed LLW disposal facility in the U.S.

Waste Control Specialists has two standard types of MCC: (1) cylindrical: 6 foot (') 8 inches (") D x 9' 2" H (internal dimension) 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 H-3 shows wastes being placed in a rectangular MCC.

H.5.1.3 Containers with Capacity of 8.4 Cubic Meters

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 <u>capacity of 8.4 m3 each (11 yards3), two soft-side containers will fit in a standard rectangular MCC</u> (allowing 2" extra on all four sides and 2" extra on top, between the shipping container and the walls of the rectangular MCC). Additional details on these 8.4 m3 containers is provided in Section 7.

[71] Much of this information is from the WCS website at http://www.wcstexas.com/about-wcs/environment/

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

Figure H-3 Rectangular MCCs inside a Disposal Cell with Components of Multi-Barrier Liner are Visible in the Background

Waste Control Specialists is equipped to receive wastes by truck and by rail. For rail, they have a specific receiving building that straddles the railhead, and their own locomotive to bring wastes on site from nearby Eunice, New Mexico.

H.5.2 Key Regulatory Requirements

Texas is a U.S. Nuclear Regulatory Commission (NRC) Agreement State[72] and the Texas Commission on Environmental Quality (TCEQ) 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, TCEQ used their state regulations that are equivalent to the U.S. NRC's 10 CFR 61 licensing requirements. After a detailed licensing process, TCEQ issued a Radioactive Materials License to WCS to dispose of LLW in 2009. TCEQ 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 mixed LLW (MLLW)

The FWF is licensed for up to 26,000,000 ft3 (~736,000 m3) and 5,600,000 curies total of wastes. <u>The licensed volume limit is roughly three times larger than the volume of SLAW (204,400 m3).</u> 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 H-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 (cite). In post-closure, the DOE will own the immobilized SLAW wastes, whether disposed at the IDF or at the WCS.

All other regulatory requirements applicable to the WCS are addressed in Section 4.0

H.5.3 Waste Acceptance Criteria

As used here, Waste Acceptance Criteria (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 TCEQ 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 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.

H.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

[72] 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.

- 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.

H.5.3.2 Land Disposal Restrictions

Need short discussion LDRs and fact that WCS cannot accept for disposal wastes with LDRs

H.5.3.3 Waste Classification

The FWF is authorized 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; Greater-than-Class- C (GTCC) wastes are currently prohibited. The two tables from the *FWF Generators Handbook* are copied and inserted here as Table H-7 for long-lived nuclides and Table H-8 for short lived nuclides.

Table H-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/m³	[1]	Ci/m³	8	Ci/m³
C-14 in Activated Metals	8	Ci/m³	[1]	Ci/m³	80	Ci/m³
Ni-59 in Activated Metals	22	Ci/m³	[1]	Ci/m³	220	Ci/m³
Nb-94 in Activated Metals	0.02	Ci/m³	[1]	Ci/m³	0.2	Ci/m³
Tc-99	0.3	Ci/m³	[1]	Ci/m³	3	Ci/m³
I-129	0.008	Ci/m³	[1]	Ci/m³	0.08	Ci/m³
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 H-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/m³	[3]	Ci/m³	[3]	Ci/m³
H-3	40	Ci/m³	[3]	Ci/m³	[3]	Ci/m³
Co-60	700	Ci/m³	[3]	Ci/m³	[3]	Ci/m³
Ni-63	3.5	Ci/m³	70	Ci/m³	700	Ci/m³
Ni-63 in Activated Metals	35	Ci/m³	700	Ci/m³	7,000	Ci/m³
Sr-90	0.04	Ci/m³	150	Ci/m³	7,000	Ci/m³
Cs-137	1	Ci/m³	44	Ci/m³	4,600	Ci/m³

[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.

H.5.4 Classification of Waste Forms for Disposal

Table I and Table II (reproduced as Tables H-7 and H-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.
- 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.

H.5.4.2 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 0.054 Ci/m3 (roughly one one-hundredth the limit) (HOW TO CITE STATISTICS FROM THE FEED VECTOR??)
2. Disposal of I-129 is not an issue at WCS: The Class C limit for I-129 is 0.08 Ci/m3, whereas the average concentration of I-129 is in the Feed Vector is 0.000054 Ci/m3 (roughly one one-thousandth the limit)
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.

H.5.4.3 Classifying the Final Waste Forms Using WCS Radiological WAC

Table H-9 presents the list of wastes being considered for disposal at the WCS FWF.

Table H-9 Wastes to be Disposed at WCS

	Container	**Total Volume m3** **Average Volume/month m3**	**Containers/month** for 337 months
Primary Wastes			
2f – Grout with LDR pretreat & 99% Sr-90 removed	8.4 m3 bag in box	367,900 1092	130
2g2 - Grout with LDR pretreat	8.4 m3 bag in box	367,900 1092	130
3b - Steam Reformed Granular	8.4 m3 bag in box	245,300 728	87
Secondary Wastes Secondary solid wastes (SSW) Pretreatment wastes (PW)			
SSW from 1c (cannister vit to IDF)	B-25 box	TBD	TBD

	Container	Total Volume m3 Average Volume/month m3	Containers/month for 337 months
SSW from 1g (bulk vit to IDF)	B-25 box	TBD	TBD
PW with Tc-99 dried/grouted PW with I-129 dried/grouted From 2e2 (grout to IDF)	B-25 box B-25 box	TBD TBD	TBD TBD
SSW from 3b (steam granular to WCS)	B-25 box	TBD	TBD

Information provided by the Feed Vector, combined with information on the characteristics of the final WFs (Section 6.3.1, 6.3.2 and 6.3.3) can be used to determine the classification (Class A, B, C or GTCC) of the final WF for each month. This can be demonstrated using one long-lived nuclide in the Feed Vector for the WTP PT for April 2060, information about the grout WF and WCS's Table I classification table:

- Table H-2 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 H-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 will be 4.94E-02/3 = 1.64E-02
- The fractional contribution of all the Table I long-lived nuclides can be calculated in this way, and if the sum of those fractions is less than 1, (but greater than 0.1), then 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 classification (Class C in this case), unless the Table II classification is higher.

H.5.4.4 Classifying Primary WFs for Disposal from 337 Months of Immobilization (and the magic of the EXCEL Workbook)

The Feed Vector data is contained in a large EXCEL Spreadsheet. A companion EXCEL workbook has been setup that (1) accesses the Feed Vector data, (2) contains WCS's Table I and Table II radiological WAC for classifying wastes for disposal, and (3) utilizes the logic of calculating the sum of fractions and determining the waste classification (Class A, B, C or GTCC) from Table I and Table II. 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.

Using the Feed Vector Data, data on the characteristics of the final WF and the EXCEL Workbook, the classification of the final WFs for three variants was determined and is presented in Table H-10.

Table H-10 Classification of Primary WFs to be Disposed at WC S(measured as number of months of output from WTP PT and LAW PS)

Variant	Class A	Class B	Class C	GTCC
2f – Grout with LDR pretreat & 99% Sr-90 removed (1.8 m3 & 1770 kg/m3)	406	2	33	0
2g2 - Grout with LDR pretreat (1.8 m3 & 1770 kg/m3)	0	408	33	0
3b - Steam Reformed Granular (1.2 m3 & 800 kg/m3)	0	302	130	9

H.5.4.5 How Strontium-90 Concentrations Affect Waste Classification

As discussed above, 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, which causes almost all the grouted WF to be classified as Class B MLLW. Because of the $5,000 per cubic meter cost differential between Class A MLLW disposal and 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. Current disposal fees are discussed below. Results of the analysis are summarized in Table H-11.

Table H-11 Classification Grout with Strontium-90 Removal (1770 kg/m3 and 1.8 multiplier) (measured as number of months of output from WTP PT and LAW PS)

% 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

H.5.4.6 Classifying Secondary Wastes for Disposal

Secondary Solid Wastes and PWs will be disposed at WCS as a component of variants 2f, 2g2 and 2e2. The PWs will contain Tc-99 and I-129, and it is assumed that the Tc-99 and I-129 would be managed as separate waste streams. An analysis was undertaken to determine the limiting criteria (transportation or the WAC at WCS) and it is assumed that these waste concentrations would be generated up to that limit. It is further assumed that the Tc-99 and I-129 would be fairly uniformly distributed in a grout matrix, and that the wastes would be shipped in high weight capacity B-25 box with an internal volume of 2.5 m3. As shown in Table H-12, for both nuclides, the WAC is limiting – therefore, the PWs will be generated up to the WAC limit, grouted, shipped in a B-25 box and disposed at WCS as Class C LLW.

Table H-12 Limiting Criteria for Shipping and Disposal of Tc-99 and I-129 (assuming 2.5 m3 shipping container)

	A_2 value for shipping	WCS Class C limit for disposal	Limiting criteria, assuming uniform distribution in grout in a 2.5 m3 box
Tc-99	24 Ci	3 Ci/m3	3 Ci/m3 (maximum, with no other nuclides present)
I-129	unlimited	0.08 Ci/m3	0.08 Ci/m3 (maximum, with no other nuclides present

H.5.4.7 Conclusions from Classifying the Waste Forms for Disposal at WCS

The key take-away from this detailed analysis is that essentially all final WFs (steam reformed granular mineral product and grout) can be accepted for disposal at the WCS disposal facility (LDR issues will need to be addressed).

The low specific weight of the granular waste (800 kg/m3 (50 lb/ft3)) in variant 3b did result in a relatively small number of months (9 months) in which the steam reformed granular WF from the WT PT will be classified as GTCC MLLW[73]. Given this knowledge, in practice, averaging would be used to prevent the generation of GTCC wastes.

For the grout WF, and Sr-90 removal (variant 2f), almost all wastes shift from higher-cost Class B MLLW to lower cost Class A MLLW. Strontium-90 removal does not change the number of months that produce Class C MLLW (33 months), because it is the concentration of transuranic (TRU) nuclides that causes these 33 months of SLAW to be Class C, and removal of the Sr-90 does not affect the specific activity of the TRUs.

H.5.5 Costs Considerations for Disposal

The DOE and WCS are working to define appropriate unit costs for disposal of SLAW waste forms at WCS. The unit costs in the Indefinite Delivery/Indefinite Quantity contract between DOE/EM and WCS for April 12, 2018 through April 11, 2023 will provide a point of departure for the discussions.

H.5.6 Summary of WCS

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.

The detailed characteristics of the final immobilized WFs can be derived from the detailed characteristics of the Feed Vector by assuming a conservation of radionuclide mass and the knowledge of three parameters that describe the final WF.

Waste Control Specialists, LLC is a treatment, storage and disposal company dealing in radioactive, hazardous, and mixed wastes. Their primary facilities are located 35 miles west of Andrews, Texas and 5 miles east of Eunice, New Mexico. At WCS, the FWF is designed, licensed, and constructed for federal waste disposal, for wastes from the DOE and other federal agencies. The combined characteristics (no drinking water aquifer, thick red clay beds, 2-m (7 ft) -thick multi-barrier liner and MCCs) give WCS and the FWF the most robust design of any Agreement State licensed LLW disposal facility in the U.S.

[73] For a fixed curie inventory of transuranics, high specific weight WFs (e.g., 1800 kg/m3) result is lower specific activities of transuranics (measured as nanocuries per gram of waste) and low specific weight WFs (e.g., 800 kg/m3) will result in higher specific activities of transuranics, measured as nanocuries per gram.

The licensed volume of the FWF at WCS (~736,000 m3) is roughly three times larger than the volume of SLAW (204,000 m3).

The DOE has signed an Agreement to take ownership of the FWF after its closure (cite). In post-closure, the DOE will own the immobilized SLAW wastes, whether disposed at the IDF or at the WCS.

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 0.054 Ci/m3 (roughly one one-hundredth the limit)

Disposal of I-129 is not an issue at WCS: The Class C limit for I-129 is 0.08 Ci/m3, whereas the average concentration of I-129 is in the Feed Vector is 0.000054 Ci/m3 (roughly one one-thousandth the limit)

The key take-away from this detailed analysis is that all final WFs (steam reformed mineral product and grout) can be accepted for disposal at the WCS disposal facility (assume LDR issues are addressed).

APPENDIX I. EXPANDED DISCUSSION – TRANSPORTATION CONSIDERATIONS

I.1 INTRODUCTION

This Section develops the programs that will be needed to transport primary and secondary WFs from the Hanford Reservation to the WCS disposal facilities in west Texas.

I.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.

I.3 KEY REGULATORY CONSIDERAITONS

The NRC *regulates the packaging* for the transport of radioactive materials. The 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*.

Radioactive materials are transported routinely and safely every day. As a relevant example – DOE completed ~ 5,500 shipments of radioactive materials in Fiscal Year (FY) 2016 with no reportable accidents (Office of Packaging and Transportation Annual Report FY2016). One of the reason for this safety record is that the transport of radioactive materials is very regulated.

I.3.1 10 CFR 71 Packaging and Transportation of Radioactive Material

The NRC's 10 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),[74] materials may be shipped in industrial packages (IPs) that are exempt from NRC package certification (but not exempt from DOT requirements)
- Materials that exceed the LSA limits, but are below the "A_2" content limit[75], must be shipped in Type A packaging, and where

[74] Low Specific Activity material means radioactive material with limited specific activity that is nonfissile or is excepted 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).

[75] The A_2 value is the maximum amount of radioactive material (measured in becquerels or curies), other than special form, LSA, and Surface Contaminated Object materials, permitted in a Type A package. This value is either listed in 10 CFR Part 71, Appendix A, Table A-1, or may be derived in accordance with the procedures prescribed in 10 CFR Part 71, Appendix A. (10 CFR 71.4)

- Higher-activity content materials that exceed the LSA limits, and that exceed the A_2 content limit, must be shipped in Type B packaging, which meets the most stringent criteria (except for the air-transport criteria).

All packages for shipping radioactive material (IP or Type A or Type B) must be designed and prepared so that under conditions normally incident to transportation the radiation level does not exceed 2 millisievert/hour (mSv/h) (200 millirem/hour (mrem/h)) at any point on the external surface of the package, and the transport index does not exceed 10. (10 CFR 71.47)

I.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 is dispersible in a transportation accident, and special form is not dispersible. Special form radioactive material means radioactive material that (1) is either a single solid piece or is contained in a sealed capsule that can be opened only by destroying the capsule, (2) has a certain minimum size and (3) it satisfies the rigorous requirements of 10 CFR 71.75. Special form materials are not easily dispersible. If a material is not special form, then the material is normal form. Sealed radioactive sources are an example of special form material. Most radioactive materials are normal form.

The methodology and tables for determining if the amount of activity in a container exceeds the A_2 limit are presented in Appendix A to 10 CFR 71.

I.3.1.2 Shipping in Industrial Packages

"Low specific activity" radioactive materials may be shipped as NRC-defined LSA material in IPs that are exempt from NRC certification, if the specific activity (the activity per unit mass) of the WFs is low enough, and other requirements are met. As discussed later, the LSA criteria are linked to the A_2 quantity. The three types of LSA materials are discussed in detail in Section 7.6.

I.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 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 that are 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 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.

I.3.4 DOE Regulations and Orders

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 OPT flow from 41 Code of Federal Regulations (CFR) 109-40, Transportation and Traffic Management, and 49 CFR 173, Department of Transportation, 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.

I.3.5 National Environmental Policy Act

The National Environmental Policy Act (NEPA) 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 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
- **Radiological Impacts of Routine Transportation** - Dose to a maximally exposed individual and the projected population dose
- **Non-radiological Impacts of Transportation Accidents** - Statistical number accidents and fatalities from a proposed transportation program, and
- **Radiological Impacts of Transportation Accidents** - Statistical doses from a hypothetical accident.

This NADA study is not a NEPA EIS, and the relative hazards from the proposed shipping program are identified through analogue NEPA studies of the safety of rail transport of radioactive materials (Section 7.8).

I.4 NATURE AND VOLUME OF WASTES TO BE SHIPPED

The nature and volume of the wastes to shipped were described in Section 6.3 (WASTE FORM CHARACTERISTICS) and Section 6.5.4 (Classification of Waste Forms for Disposal). For readability, a key table from Section 6 is reproduced here as Table I-1 Nature and Volume of Wastes to be Shipped to WCS. As discussed in Section 6, the primary waste forms will be shipped in 8.4 m3 containers.

Table I-1. Nature and Volume of Wastes to be Shipped to WCS

	Container	**Total Volume m3** **Average Volume/month m3**	**Containers/month** for 337 months
Primary Wastes			
2f – Grout with LDR pretreat & 99% Sr-90 removed	8.4 m3 bag in box	367,900 1092	130
2g2 - Grout with LDR pretreat	8.4 m3 bag in box	367,900 1092	130
3b - Steam Reformed Granular	8.4 m3 bag in box	245,300 728	87
Secondary Wastes Secondary solid wastes (SSW) Pretreatment wastes (PW)			
SSW from 1c (cannister vit to IDF)	B-25 box	TBD	TBD
SSW from 1g (bulk vit to IDF)	B-25 box	TBD	TBD
PW with Tc-99 dried/grouted PW with I-129 dried/grouted From 2e2 (grout to IDF)	B-25 box B-25 box	TBD TBD	TBD TBD
SSW from 3b (steam granular to WCS)	B-25 box	TBD	TBD

I.5 LAG STORAGE FACILITY

Figure I-1 show the monthly output of 8.4 m3 containers of grout. To even-out the high and low production months shown in Figure I-1, a “lag storage facility” will be built at the immobilization facility, so that a constant volume of waste is shipped and disposed each month. Shipping a constant volume is cost effective, allowing uniform staffing, equipment and shipping capacity.

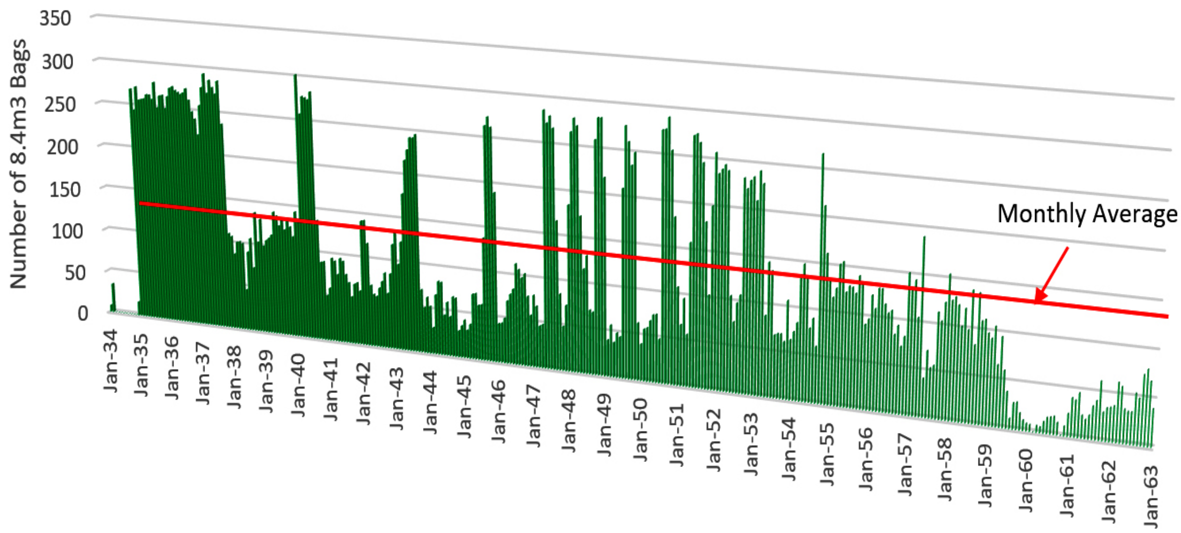

Figure I-1. Number of 8.4 m3 Containers of Grout Produced per Month

Given the average amount of grout produced each month (1092 m3 from Table I-1), the average number of 8.4 m3 containers of grout per month will be 130 containers. To determine the capacity of the lag storage facility, a simple program was setup, and for each month that produces more than 130 containers of grout, the excess is "counted" by the program, and for each month that the produces less than 130 containers of grout, the deficiency is removed from that count.

Based on this simple program, Figure I-2 shows the number of 8.4 m3 containers in the lag storage at any point in time. Figure I-2 shows that the lag storage facility for grout will need to have a capacity of ~6000 containers.

The analysis to determine the capacity of a lag storage facility for the steam reformed WF can be derived by multiplying the numbers of 8.4 m3 containers in Figure I-2 by 0.67 (= 1.2 for steam divided by 1.8 for grout), such that the lag storage facility for the steam reformed granular WF will need to have a capacity of ~ 4000 containers.

In analyzing the data, approximately one-half of this storage capacity is needed to provide additional feed for the last five years of operation. Using two average shipping rates would greatly reduce the size of the storage facility – with one average shipping rate from January 2035 to August of 2058 and a second average rate from August 2058 to January of 2016.

Figure I-2. Number of 8.4 m3 Containers of Grout in Lag Storage

I.6 LOW-SPECIFIC ACTIVITY DETERMINATION AND PACKAGE REQUIREMENTS

As noted earlier, LSA material means radioactive material with limited specific activity that is nonfissile or is excepted under 10 CFR 71.15, and satisfies the descriptions and limits for LSA set forth in 10 CFR 71.4. The NRC defines three categories of LSA: LSA-I, LSA-II and LSA-III. Working in tandem, the DOT defines the packaging requirements for LSA materials.

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 … more details on LSA-II needed here … other material in which the activity is distributed throughout and the **average specific activity is less than 10^{-4} A_2/gram for solids** and gases, and 10^{-5} A_2/gram for liquids

LSA-III includes solids (e.g., consolidated wastes, activated materials), *excluding powders*, 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 2×10^{-3} A_2/gram**." (10 CFR 71.4)

Other criterial that the three categories of LSA materials must meet include:

- External radiation at any point on the external surface of the shipping package must not exceed 2 mSv/h (200 mrem/h) (10 CFR 71.47(a))

- The material must have an external radiation dose less than or equal to 10 mSv/hour (1 rem/hour) at a distance of 3 m (10 ft) from the unshielded material (10 CFR71.14(b)(3)(i)) and 49 CFR 173.427).

Calculating the A_2 Value for a Mixture of Radionuclides

The formula for calculating the A_2 for a mixture of radionuclides is presented in Figure I-3, which is coped from the NRC's Appendix A of 10 CFR 71.

As a potentially bounding assessment of the A_2 value, 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 A_2 calculation for wastes from November 2035 is presented in Table I-2.

Table I-2. A2 Calculation using Concentrations from November 2035 from WTP PT

Symbol	**Element**	**A_2 (Ci)** from Apx A 10 CFR 71		Concentration (Ci/m3) from Feed Vector	fraction contribution f(i)	**f(i)/A_2(i)**
Ac-227 (a)	Actinium	2.40E-03		6.24E-06	1.53E-06	6.39E-04
Am-241	Americium	2.70E-02		1.71E-01	4.20E-02	1.56E+00
Am-243 (a)		2.70E-02		6.02E-05	1.479E-05	5.48E-04
C-14	Carbon	81		3.77E-03	9.26E-04	1.14E-05
Cd-113m	Cadmium	14		2.75E-03	6.76E-04	4.83E-05
Cm-242	Curium	0.27		6.11E-05	1.501E-05	5.56E-05
Cm-243		2.70E-02		3.04E-06	7.47E-07	2.77E-05
Cm-244		5.40E-02		4.85E-05	1.191E-05	2.21E-04
Co-60	Cobalt	11		7.69E-05	1.889E-05	1.72E-06
Cs-134	Cesium	19		4.26E-10	1.047E-10	5.51E-12
Cs-137 (a)		16		4.31E-02	0.0105879	6.62E-04
Eu-152	Europium	27		9.85E-05	2.42E-05	8.96E-07
Eu-154		16		1.89E-03	4.64E-04	2.90E-05
Eu-155		81		2.86E-04	7.03E-05	8.67E-07
I-129	Iodine	Unlimited		1.44E-04	3.54E-05	0.00E+00
Nb-93m	Niobium	810		1.02E-02	2.51E-03	3.09E-06
Ni-59	Nickel	Unlimited		4.50E-04	1.11E-04	0.00E+00
Ni-63		810		2.39E-02	5.87E-03	7.25E-06
Np-237	Neptunium	5.40E-02		1.45E-04	3.562E-05	6.60E-04
Pa-231	Protactinium	1.10E-02		9.71E-06	2.385E-06	2.17E-04
Pu-238	Plutonium	2.70E-02		3.28E-04	8.058E-05	2.98E-03
Pu-239		2.70E-02		3.81E-03	0.000936	3.47E-02
Pu-240		2.70E-02		9.70E-04	0.0002383	8.83E-03

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)**
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
U-238 (all lung absorption types) (d), (e), (f)		Unlimited	2.62E-05	6.436E-06	0.00E+00
Zr-93	Zirconium	Unlimited	1.06E-02	0.002604	0.00E+00
		Sum Ci/m3 =	4.07E+00	1.00E+00	
			Sum f(i)/A_2(i) =		1.68E+00
			A_2 for mix (Ci) =		**5.97E-01**

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

where f(i) is the fraction of activity for radionuclide I in the mixture, and A_2(i) is the appropriate A_2 value for radionuclide I.

Figure I-3. Formula for Calculating the A2 for a Mixture of Radionuclides

Classifying the Grout Waste Form as LSA-III

The criteria for LSA-III specifically mentions concrete WFs, and the grout 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 I-2). With an activity multiplier of 0.56 (=1/1.8) for grout and a specific density of 1770 kg/m3 (see Table 6-6), the specific activity of the grout is 1.2E-06 Ci/gram (= (4.07 x 0.56) / 1770,000).

For the SLAW from the WTP PT for November 2035, the A_2 is 5.97E-01 (Table I-2) and 2×10^{-3} of the A_2/gram is 1.19E-03 Ci/gram. **Therefore, the specific activity of the grout 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.

However, the A_2 for other months also need to be calculated, because the A_2 is not intuitive and because the bounding case for disposal may not be the bounding case for calculating the A_2.

Other criteria for LSA-III:

- 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 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 one-half of those curies, it is assumed the grout would easily meet both dose-based criteria. Microshield calculations will 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.) – yes, grout will do this.
- The radioactive material is relatively insoluble, or it is intrinsically contained in a relatively insoluble material, so that even under loss of packaging, the loss of radioactive material per package by leaching, when placed in normal pH water for 7 days, would not exceed 0.1 A_2. It is assumed that the large monolith of grout, with a limited surface area, limited activity, and a high pH would meet this criterion. Additional analysis will be conducted to validate this assumption.

Classifying the Steam Reformed Granular Waste Form as LSA-II

The criteria for LSA-III specifically excludes "powders." However, the steam reformed 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 criteria for LSA-II is an order of magnitude stricter (< 10^{-4} A_2/gram) than the criteria for LSA-III classification.

For the SLAW from the WTP PT for November 2035, the summed activity is 4.07 Ci/m3 (Table I-2). With a curie multiplier of 0.83 (=1/1.2) for steam reformed granular WF and a specific density of 800 kg/m3 (see Table 6-5), therefore, the specific activity of the steam reformed granular WF is 4.2E-06 Ci/gram (= (4.07 x 0.83) / 800,000). For the SLAW from the WTP PT for November 2035, the A_2 is 5.97E-01 (Table I-1) and 10^{-4} of the A_2/gram is 5.97E-05 Ci/gram. **Therefore, the specific activity of the steam reformed 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.

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 one-half of those curies, it is assumed the steam reformed waste form would meet both dose-based criteria. Microshield calculations will be done in the future to confirm this assumption.
- The radioactivity is essentially uniformly distributed – yes, the steam reformed product will do this.

Package Requirements for Shipping LSA-II and LSA-III Materials

The DOT requires that LSA material must be transported in packages meeting Type IP-1, Type IP-2 or Type IP-3 criteria (49 CFR 173.411). The DOT in 49 CFR 173.427, Table 6 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 73.465 (c) (free drop test) and (d) (stacking test)* must prevent the (i) loss or dispersal of the radioactive contents, and (ii) a significant increase in the radiation levels.

One of the tests, the stacking test, requires that Type IP-2 package 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.

For shipping non-combustible LSA-II and LSA-III solids, there is no limit to the amount of activity in any single conveyance (49 CFR 173.427 Table 5).

Soft Side Container

Figure I-4 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”L x 88”W x 53”H (filled volume will be 8.4 m3, which will half-fill a MCC at WCS).

Figure I-4. Example of Soft Side Container for Shipping LSA Materials (need permission of PACTEC)

Reusable Steel Box

To provide a rigid form for the grout, to facilitate handling, and to increase public confidence, the IP-2 soft side containers will be managed in reusable steel boxes. To do this, the soft side container will be placed in the box, filled with grout or steam reformed mineral product, transferred to a gondola railcar, shipped to WCS; where the soft side will be off-loaded for disposal. The steel box is not required to meet DOT packaging requirements. The reusable box will then be transported back to Hanford for reuse. Conceptually, the steel box might look similar to the steel box shown in Figure I-5, with a shallower lid. Finally, Figure I-6 shows an example of a 2.5 m3 B-25 box which will be used to transport the secondary solid wastes and the pretreatment wastes.

Figure I-5. Example of Reusable Steel Box (actual box might have shallower lid and be lighter weight) (need permission of CTI)

Figure I-6. Example of B-25 Box (need permission of CTI)

I.7 PROGRAM TO TRANSPORT WASTE TO WCS BY RAIL

All wastes will be shipped on gondola railcars. Words to justify rail over truck here. Table I-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 I-4 summarizes the number of gondola railcars needed each month to transport the average monthly amount of each WF.

Table I-3. Containers per Gondola Railcar

WASTE FORM	SPECIFIC WEIGHT	CONTAINER SIZE M3	WEIGHT / CONTAINER (WASTE + 10%)	CONTAINERS / GONDOLA
Primary Wastes				
• Grout	1770 kg/m3 (110 lb./ft3)	8.4	16,350 kg ~ 36,000 lb	5
• Steam Reformed granular	800 kg/m3 (50 lb/ft3)	8.4	7,392 kg 16,260 lb	12
Secondary Wastes				
• Secondary solid wastes (SSW)	1770 kg/m3 (110 lb./ft3)	2.5	4,868 kg 10,700 lb	18
• Pretreatment wastes (PW)	1770 kg/m3 (110 lb./ft3)	2.5	4,868 kg 10,700 lb	18

Table I-4. Gondola Railcars per Month

WASTE FORM	Container	Volume/month m3	Containers/month 337 months	Railcars/month
Primary Wastes				
• 2f – Grout with LDR pretreat & Sr-90 removed	8.4 m3 bag in box	1092	130	26
• 2g2 - Grout with LDR pretreat	8.4 m3 bag in box	1092	130	26
• 3b - Steam Reformed Granular	8.4 m3 bag in box	727	87	8
Secondary Wastes				
• SSW from 1c (cannister vit to IDF)	B-25 box	TBD	TBD	TBD
• SSW from1g (bulk vit to IDF)	B-25 box	TBD	TBD	TBD
• PW with Tc-99 dried/grouted • PW with I-129 dried/grouted • From 2e2 (grout to IDF)	B-25 box B-25 box	TBD TBD	TBD TBD	TBD TBD
• SSW from 3b (steam granular WCS)	B-25 box	TBD	TBD	TBD

The rail route show in Figure I-7 was obtained with TRAGIS, the ORNL routing tool assuming dedicated train. The route starts at Richland, WA railnode and ends at Eunice, NM railnode. These were the closest available railnodes to Hanford and WCS respectively. The total distance is 2231.6 mi. The calculated travel time by dedicated train is 78.5 hrs (3.3 days) hours. The Figure I-7 shows the route as well as the railroad networks. Note that the other routes are possible.

The route includes three rail companies: BNSF, UP, and TXN. The information on the distance traveled is summarized below. There are three transfers along the route:

- From UP to BNSF in Cheyenne, WY. Distance on UP is 1309 miles.
- From BNSF to UP in Sweetwater, TX. Distance on BNSF is 856 miles.

- From UP to TXN in Monahans, TX. Distance on TXN is 67 miles.

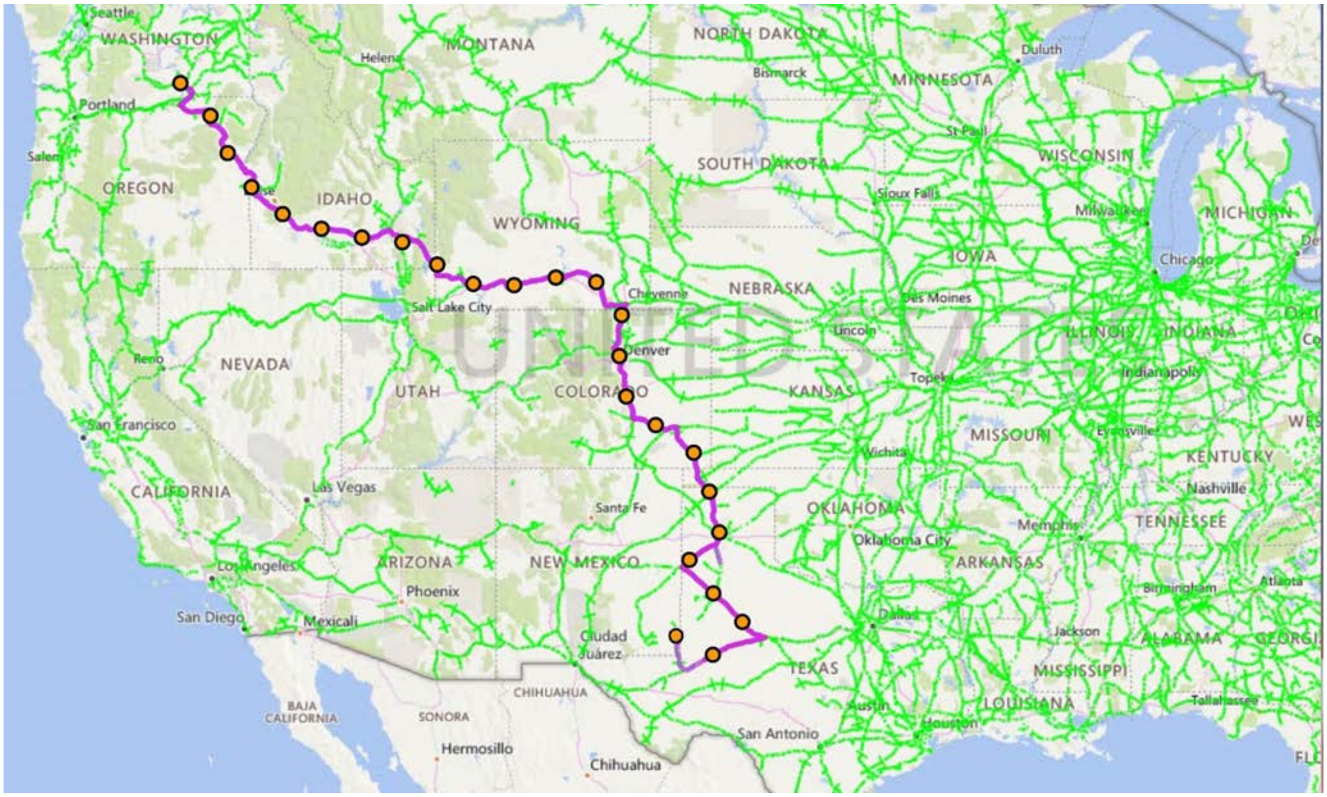

Figure I-7. Dedicated Train Rail Route

I.8 RELATIVE HAZARDS FROM SHIPPING PROGRAM [work in progress]

- Points relevant to shipping risks:
  - Shipping solid materials (no liquids, no gases)
  - Specific activity meets NRC definition of “low specific activity materials”
  - Shipping by rail
  - Shipped in DOT IP-2 containers in reusable steel boxes
  - Number shipments is low (26 railcars making 4,400 mile roundtrip per month)

- For accident frequency – will review risk of accidents per freight car mile

- For radiological dose - will review analogue studies of shipping radioactive material by rail

For programmatic risk / State concerns – plan to review analogue situations

I.9 SUMMARY

APPENDIX J. EXPANDED DISCUSSION – REGULATORY COMPLIANCE

J.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 Energys' (DOE) radioactive waste management activities as prescribed under various DOE orders, including DOE Order 435.1 (DOE O 435.1), "Radioactive Waste Management".[76] DOE O 435.1 was promulgated under Atomic Energy Act of 1954, as amended. DOE is the responsible party for the safe management and final disposal of all radioactive wastes arising from its operations. The objective of the activities required under this order is to ensure that the waste is managed in a manner that is protective of worker and public health and safety, and the environment.

DOE O 435.1 requires that radioactive waste at DOE sites be managed to comply with applicable Federal, State, and local laws and regulations as well as Executive Orders and other DOE directives. Based on the guidance provided in DOE M 435.1-1, the regulations that may be applicable to the Hanford Site for the supplemental treatment of low activity waste, at a minimum, include:

- Resource Conservation and Recovery Act (RCRA) requirements (40 CFR Parts 260—273) for mixed low-level waste[77] (See Ref. 1);
- Applicable sections of Washington State (WA) regulations (WAC 173-303) that implement RCRA requirements (See Ref. 2);
- Clean Air Act (CAA) implementing regulations at 40 CFR Subchapter, Parts 50-97 (See Ref. 3);
- Applicable sections of WA air regulations to include, criteria pollutants (WAC 173-400), toxic air pollutants (TAPs) (WAC 173-460), and radioactive air pollutants (WAC 246-247) (See Ref. 4 to 6);
- Occupational Radiation Protection requirements (10 CFR Part 835) for oversight of radioactive waste management facilities, operations, and activities;
- Toxic Substances Control Act (TSCA) requirements (40 CFR Part 761) for low-level waste containing polychlorinated biphenyls, asbestos, or other such regulated toxic components[78] (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

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

[77] 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.

[78] 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.

J.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.[79] The Hanford waste slated for disposal as low activity waste must be determined to meet the Waste Incidental to Reprocessing (WIR) criteria in DOE M 435.1-1(See Ref. 8). Incidental waste is managed under DOE's regulatory authority in accordance with the requirements for low-level waste, as appropriate.

Hanford incidental waste to be managed as low-level waste must be documented to meet the following criteria:

1. Have been processed, or will be processed, to remove key radionuclides to the maximum extent that is technically and economically practical;
2. Managed to meet the safety requirements comparable to the performance objectives set out in 10 CFR Part 61, Subpart C, Performance Objectives; and
3. Managed pursuant to DOE's authority under the Atomic Energy Act of 1954, as amended, and in accordance with the provisions included in DOE M 435.1-1, Chapter IV, provided the waste will be incorporated in a solid physical form at a concentration that does not exceed the applicable concentration limits for Class C low-level waste as set out in 10 CFR 61.55, Waste Classification, or will meet alternative requirements for waste classification and characterization as DOE may authorize.

If the waste stream is shown to meet the criteria above, then it can be disposed in a near-surface permitted facility. For Hanford's tank waste, criterion 1 is addressed through pretreatment processing of the tank waste either through the pretreatment facility within the WTP or the Low Activity Waste Pretreatment System (LAWPS) as shown in Fig. 2-1. This pretreatment processing, principally for removal of Cs and undissolved solids removes key radionuclides necessary to meet criterion 1. For this assessment, the LAW feed vector represents a post-pretreatment feed stream that has been processed to addressed criterion 1. Criterion 3 is addressed principally through the LAW processing to ultimately produce a LAW 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.

J.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

[79] 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 J-1 for the characteristic hazardous wastes, Table J-2 for listed hazardous wastes, and Table J-3 for WA State-only waste classifications, below.[80] 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,

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[80] 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 J-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 J-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 J-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)

J.3 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).[81] The tanks are considered a storage area for multiple upstream points of generation where the waste was originally produced.[82] 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.[83]

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

[81] 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.
[82] Winston, T.A.., 2013. HLVIT Applicability to Supplemental Immobilization: Impact of a RCRA New Point of Generation. RPP-RPT-52699, Rev.0.
[83] 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 years[84]. 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.[85] 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 H lists all applicable LDR standards for Hanford tank waste.

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[84] 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.

[85] 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]

J.4 REQUIREMENTS FOR AIR EMISSIONS

For the processing of the law activity waste at Hanford, toxic air pollutant controls under WA state regulations (WAC 173-460) apply.

The Clean Air Act is intended to protect and enhance the quality of the Nation's air resources so as to promote the public health and welfare and the productive capacity of its population. Section 118 of the Clean Air Act (42 U.S.C. 7401) requires each Federal agency with jurisdiction over any property or facility engaged in any activity that might result in the discharge of air pollutants to comply with all Federal, state, interstate, and local requirements with regard to the control and abatement of air pollution.

Most of the provisions of the Washington Clean Air Act mirror the requirements of the Federal Clean Air Act. The Hanford Site Air Operating Permit (AOP) regulates emissions of criteria pollutants (WAC 173-400, "General Regulations for Air Pollution Sources"), toxic air pollutants (TAPs) (WAC 173-460, "Controls for New Sources of Toxic Air Pollutants"), and radioactive air pollutants (WAC 246-247, "Radiation Protection – Air Emissions") for all Hanford site sources. Hanford operates under state license No. FF-01.

Prior to beginning any work that would result in creating a new or modified source of airborne emissions, a Notice of Construction application must be submitted to the Washington State Departments of Health and Ecology for review and approval. Ensuring adequate emission controls, emissions monitoring/sampling, and/or annual reporting of air emissions is a typical requirement for radioactive air emission sources. A New Source Review is conducted by Ecology for toxic air pollutants and criteria pollutants emissions, or the WDOH Office of Radiation Protection for radioactive emissions.

Washington air regulations were recently revised to established requirements for determining the levels of dimethyl mercury (DMM) from emission sources, and to evaluate the potential exposures to humans and the environment from this contaminant. Dimethyl mercury is an organomercury compound that is very toxic to humans. A small skin exposure of a few drops has been. Dimethyl mercury is a colorless liquid that is volatile and insoluble in water. DMM has been identified in the Hanford tanks.

The regulations require that all projects with emissions of toxics, such as DMM, in Washington Administrative Code (WAC) 173-460-150 that exceeds the de minimis levels are required to submit a first tier review. If modeled ambient concentrations exceed the acceptable source impact levels (ASIL) in WAC 173-460-150 a second tier review or Health Impacts Analysis (HIA) is required. The primary purpose of the review is to document the analysis and evaluation of the potential human health related impacts of dimethyl mercury (DMM) emissions and offsite ambient concentrations from a proposed facility. The study is intended to determine if the DMM emissions from a facility will pose an unacceptable risk to the public from an emission source. Several HIAs have been submitted to Ecology for tank farm emission sources that documented no potential health or environmental impacts from those sources.

J.5 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 J-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		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
D007	Chromium	7440-47-3	2.77 and meet 268.48 standards	0.60 mg/l TCLP and meet 268.48 standards		
D008	Lead	7439-92-1	0.69 and meet 268.48 standards	0.75 mg/l TCLP and meet 268.48 standards		
D009	Mercury	7439-97-6	0.15 mg/l TCLP and meet 268.48 standards	0.025 mg/l TCLP and meet 268.48 standards		
D010	Selenium	7782-49-2	0.82 and meet 268.48 standards	5.7 mg/l TCLP and meet 268.48 standards		
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

			Total Waste Standards	Waste Extract Standards	Technology Standards	
D034	Hexachloro ethane	67-72-1	0.055 and meet 268.48 standards	30 and meet 268.48 standards	N/A	N/A
D035	Methyl ethyl ketone	78-93-3	0.28 and meet 268.48 standards	36 and meet 268.48 standards	N/A	N/A
D036	Nitrobenze ne	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	Tetrachloro ethylene	127-18-4	0.056 and meet 268.48 standards	6.0 and meet 268.48 standards	N/A	N/A
D040	Trichloroet hylene	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 Tricholorop henol	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 concentrati on standard	No numerical or concentrati on standard		
WT02 (Washington State-only) - Toxic Dangerous Waste		NA	No numerical or concentrati on standard	No numerical or concentrati on standard		
WP01 (Washington State-only) - Persistent Dangerous Waste – Halogenated		NA	No numerical or concentrati on standard	No numerical or concentrati on standard		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
Organic Compound – Extremely 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]		
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		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
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		
Trichloromonofluoromethane		75-69-4	0.020	30		
Xylenes – mixed isomers		1330-20-7	0.32	30		
2-Nitropropane [c]		79-46-9	(WETOX or CHOXD) fb CARBN or CMBST c	CMBST [c]		CMBST [c]
2-Ethoxyethanol [d]		110-80-5	BIODG; or CMBST [d]	CMBST [d]		CMBST [d]
UHCs that are not duplicated in characteristic or listed wastes						
1,1,1,2-Tetrachloroethane		630-20-6	0.057	6.0		
1,1,2,2-Tetrachloroethane		79-34-5	0.057	6.0		
1,1-Dichloroethane		75-34-3	0.059	6.0		
1,2,4-Trichlorobenzene		120-82-1	0.055	19		
1,2-Dichloropropane		78-87-5	0.85	18		
1 ,2-trans-Dichloroethene		156-60-5	0.054	30		
1,3-Dichlorobenzene		541-73-1	0.036	6.0		
1,4-Dichlorobenzene		106-46-7	0.090	6.0		
l,4-Dioxane		123-91-1	12.0	170		
2,3,4,6-Tetrachlorophenol		58-90-2	0.030	7.4		
2,4,6-Trichlorophenol		88-06-2	0.035	7.4		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
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-Methy1cholanthrene		56-49-5	0.0055	15		
4-Bromophenylphenyl ether		101-55-3	0.055	15		
4-Chloro-3-methy1pheno1		59-50-7	0.018	14		
Acenaphthene		83-32-9	0.059	3.4		
Acenaphthylene		208-96-8	0.059	3.4		
Acetonitrile		75-05-8	5.6	38		
Acetophenone		98-86-2	0.010	9.7		
Acrolein		107-02-8	0.061	NA		
Acrylonitrile		107-13-1	0.24	84		
Alpha-BHC		319-84-6	0.00014	0.066		
Anthracene		120-12-7	0.059	3.4		
Antimony		7440-36-0	1.9	1.15 mg/l TCLP		
Benzo(a)anthracene		56-55-3	0.059	3.4		
Benzo(a)pyrene		50-32-8	0.061	3.4		
Benzo(b) fluoranthene		205-99-2	0.11	6.8		
Benzo(ghi)pery1ene		191-24-2	0.0055	1.8		
Benzo(k)fluoranthene		207-08-9	0.11	6.8		
Beryllium		7440-41-7	0.82	1.22 mg/l TCLP		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
Beta-BHC		319-85-7	0.00014	0.066		
Bis(2-ethylhexyl) phthalate		117-81-7	0.28	28		
Bromodichloro methane		75-27-4	0.35	15		
Bromomethane		74-83-9	0.11	15		
Butylbenzylphth alate		85-68-7	0.017	28		
Chloroethane		75-00-3	0.27	6.0		
Chloromethane		74-87-3	0.19	30		
Cresols (total) – substituted for each cresols isomer		1319-77-3	0.11/0.77	5.6		
Chrysene		218-01-9	0.059	3.4		
cis-l,3-dichloropropene		10061-01-5	0.036	18		
Cyanide (amenable)		57-12-5	0.86	30		
Cyanide (total)		57-12-5	1.2	590		
delta-BHC		319-86-8	0.023	0.066		
Dibenz[a,h] anthracene		53-70-3	0.055	8.2		
Dibenz (a,e) pyrene		192-65-4	0.061	NA		
Dichlorodifluoro methane		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		
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		

			Total Waste Standards	Waste Extract Standards	Technology Standards	
N,N-diphenylamine		122-39-4	0.92	13		
Naphthalene		91-20-3	0.059	5.6		
Nickel		7440-02-0	3.98	11 mg/l TCLP		
N -nitroso-di-N -propylamine		621-64-7	0.40	14		
N-nitrosomorpholine		59-89-2	0.40	2.3		
N-nitroso-N,N-dimethylamine		62-75-9	0.40	2.3		
Pentachloronitrobenzene (PCNB)		82-68-8	0.055	4.8		
Phenanthrene		85-01-8	0.059	5.6		
Phenol		108-95-2	0.039	6.2		
Polychlorinated biphenyls (PCBs)		1336-36-3	0.10	10		
p-phthalic acid		100-21-0	0.055	28		
Propionitrile		107-12-0	0.24	360		
Pyrene		129-00-0	0.067	8.2		
Silvex (2,4,5-TP)		93-72-1	0.72	7.9		
Tetrachlorodibenzo-p- dioxin (2,3,7,8-)		41903-57-5	0.000063	0.001		
Thallium		7440-28-0	1.4	0.20 mg/l TCLP		
trans-l,3-Dichloropropene		10061-02-6	0.036	18		

CAS = Chemical Abstract Service

[a] During the Regulatory Data Quality Objectives Process, 2,4-dinitrotoluene was removed from the list of contaminants of concern due to use unrelated to Hanford. Nevertheless, as long as it remains in the Hanford Tank Waste Part A application it should remain as an applicable standard.

[b] This standard is only applicable to F003 and/or F005 solvent wastes that contain any combination of one or more of the following three solvents as the only F001-F005 solvents: carbon disulfide, cyclohexanone, and methanol.

[c] This standard is only applicable to F005 solvent waste containing 2-Nitropropane as the only listed F001-F005 solvent. During the Regulatory Data Quality Objectives Process this constituent was removed from the list of contaminants of concern due to use unrelated to Hanford.

[d] This standard is only applicable to F005 solvent waste containing 2-Ethoxyethenol as the only F001-5 solvent. During the Regulatory Data Quality Objectives Process this constituent was removed from the list of contaminants of concern due to use unrelated

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 K. EXPANDED DISCUSSION: FEED VECTOR

K.1 SUMMARY

The Hanford Waste Treatment and Immobilization Plant (WTP) is a complex of facilities[4] designed to receive waste from the storage tanks and perform all pretreatment processes to prepare the waste for immobilization and then immobilize the waste in borosilicate glass[5]. A simplified diagram showing the tank farm, WTP, and other facilities required is shown in Figure K-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) 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.

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

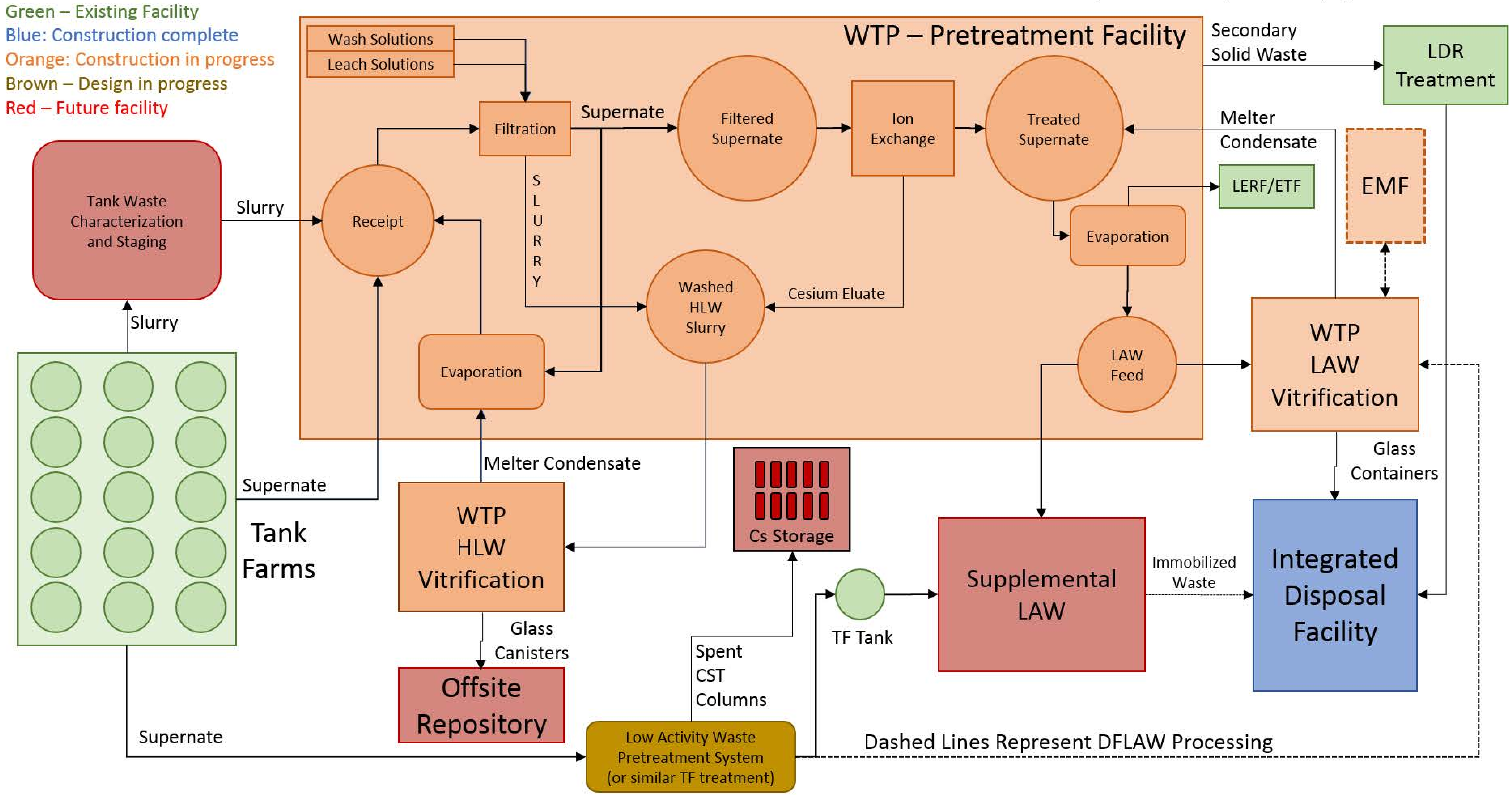

Figure K-1. Simplified Flowsheet for Immobilization of Hanford Waste during Full WTP Operation

K.2 PROCESSES FOR LAW IMMOBILIZATION AND SUPPLEMENTAL LAW IMMOBILIZATION

K.2.1 Hanford Waste Background

The Hanford site generated millions of gallons of radioactive waste during production of nuclear materials. A number of different chemical processes were used at Hanford to separate and purify plutonium, including the Bismuth Phosphate, REDuction and OXidation (REDOX), and Plutonium Uranium Extraction (PUREX) processes. In addition to the separation processes, cesium removal and other treatment processes were performed on the tank waste. As a result of the varied processes performed, the wastes stored at Hanford vary significantly in chemical and radionuclide content, although some incidental blending of the various wastes has occurred during storage[1].

The waste has been stored in 177 underground, carbon steel storage tanks. Many of these tanks are known to have developed leaks[2]; therefore, many tanks were treated to eliminate free liquid to the extent possible. The issues with the known leaks and the age of the storage tanks have led to restrictions on the type of processing allowed in the tank farms[3].

K.2.2 Baseline

The Hanford Waste Treatment and Immobilization Plant (WTP) is a complex of facilities[4] designed to receive waste from the storage tanks and perform all pretreatment processes to prepare the waste for immobilization and then immobilize the waste in borosilicate glass[5].

The tank waste will be separated into supernate and slurry in the tank farm by allowing solids to settle, then decanting supernate. Slurries will be transferred to a characterization facility to allow representative samples to be taken and any size reduction of the solids to be performed prior to transfer to the PT. Supernate from the tank farms will be transferred directly to PT or the LAWPS.

In PT, the supernate is combined with evaporated recycle (the supernate can also be sent to evaporation), and then with the slurry. Filtration is performed to separate the solids from supernate; then the concentrated solids slurry is “washed” to reduce the amount of soluble species in the slurry and can be chemically leached to remove aluminum and chromium. The solids slurry (along with the cesium extracted from the supernate) is combined with glass-former chemicals and vitrified to form a borosilicate glass in the 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 2/3 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 LAWPS facility to remove solids and cesium (using filtration and ion exchange similar to PT) with the treated supernate sent to Supplemental LAW.

K.2.3 Direct Feed Options

The 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 (not shown in Figure K-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[6].
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 LAWPS[7]. 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 K-1and shown in Figure K-2, based on the assumptions made in the One System Integrated Flowsheet[6]. These interfaces would change depending on the options chosen; for example, a grout facility would not be expected to generate a condensate stream to be treated at LERF/ETF.

Table K-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

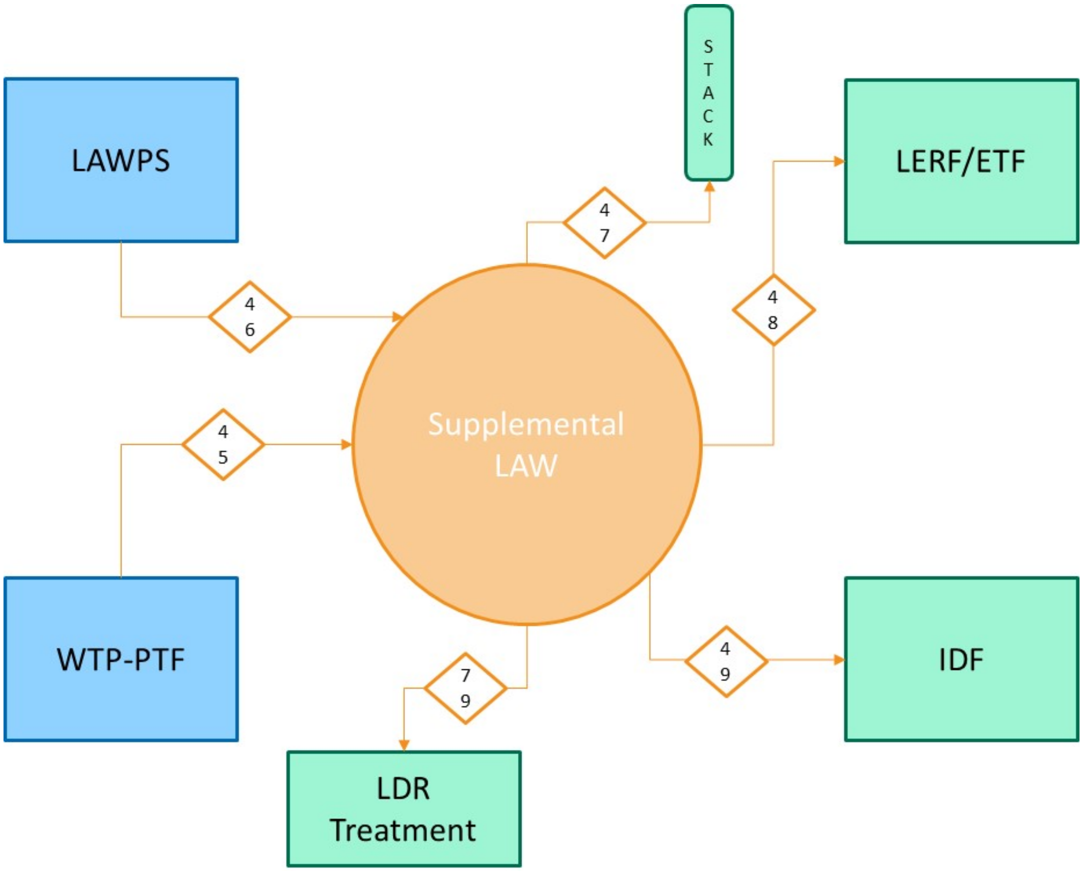

Figure L-2. Supplemental LAW Detail: Interfaces

K.2.4 Other Options Considered

As stated above, a decision on the technology for Supplemental LAW has not been made, but vitrification using melters to generated containers of immobilized LAW waste is the assumed baseline technology with disposal at the IDF.

Bulk vitrification has been evaluated in the past for LAW immobilization and is an option that will be evaluated during this review.

Grout is also mentioned as an option in the Integrated Flowsheet and will be considered as an alternate to vitrification during this review. Steam reforming will also be considered as a treatment option.
Additional options being considered during this review are to dispose the immobilized LAW at an offsite, commercial facility and options to directly treat individual tanks using a Tank Side Cesium Removal (TSCR) system to generate feed for Supplemental LAW. Offsite disposal includes sending the treated LAW supernate to a commercial vendor for immobilization and shipment to a commercial disposal facility or simply sending the immobilized product from an onsite immobilization facility to the commercial site. It is noted that treating individual tanks could lead to feed compositions to Supplemental LAW not bounded by feed vector from the Integrated Flowsheet, but it should be expected that tanks that would challenge the treatment technology would not be selected for individual treatment.

Options not selected for additional consideration during this review include:

- Immobilization of LAW into a hydroceramics[8]

- Vitrification into a non-borosilicate glass[9]
- Disposal of immobilized LAW at other DOE sites

K.3 SUPPLEMENTAL LAW FEED VECTOR

The Supplemental LAW feed vector [7] calculated for the One System River Protection Project Integrated Flowsheet [6] is being used in the evaluation of the feasibility of proposed 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 that the values shown.

The varied methods used during the nuclear material separations processing at Hanford resulted in waste that varies significantly in composition. Typically, these varying waste types are segregated across the tank farms (although some incidental blending has occurred and will occur during retrieval) which can result in large swings in feed composition to the Supplemental LAW facility, as shown in Figure K-3, Figure K-4, Figure K-5, and Figure K-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 facility[6] from PT in the Integrated Flowsheet.

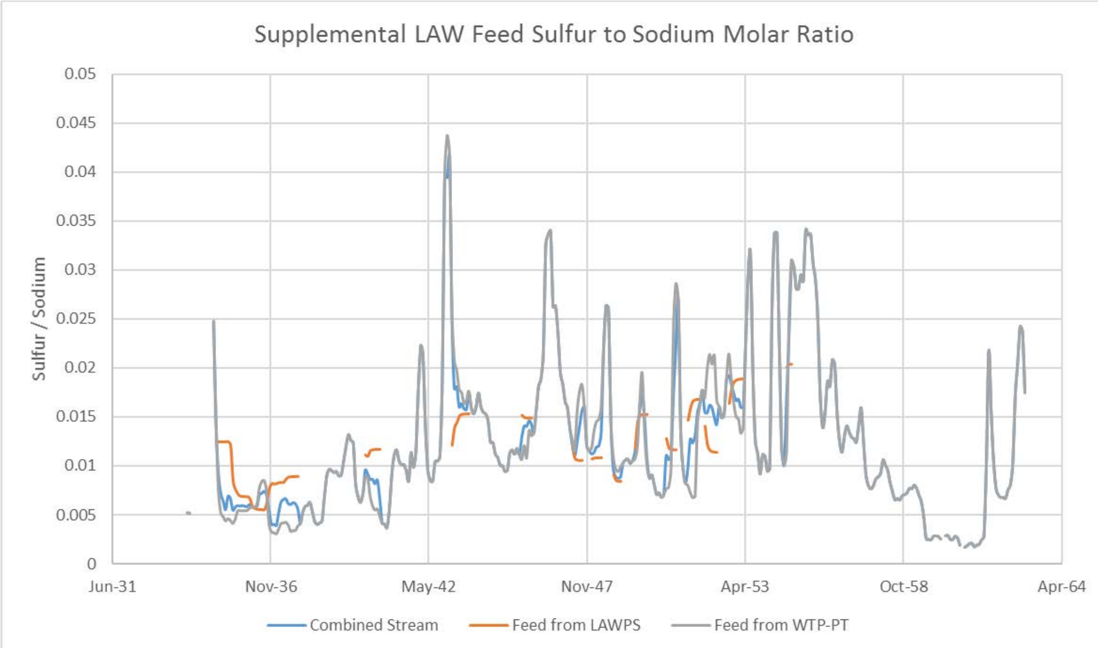

Figure K-3. Sulfur to Sodium Ratio

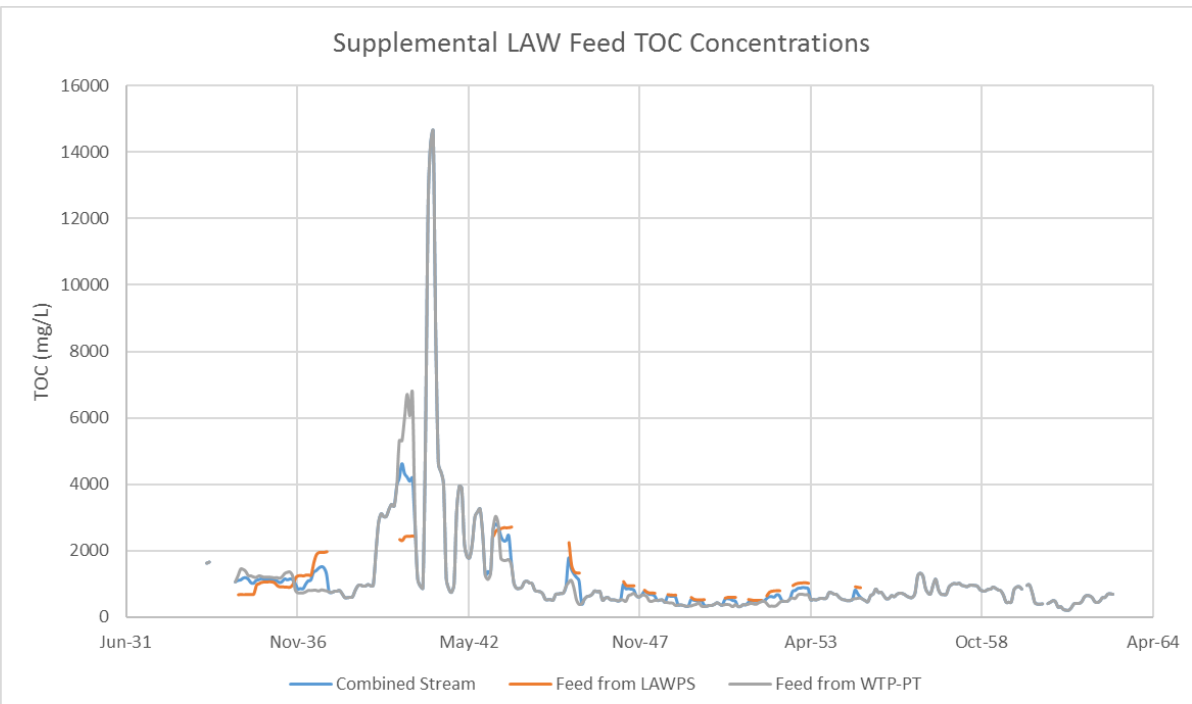

Figure K-4. TOC Concentration

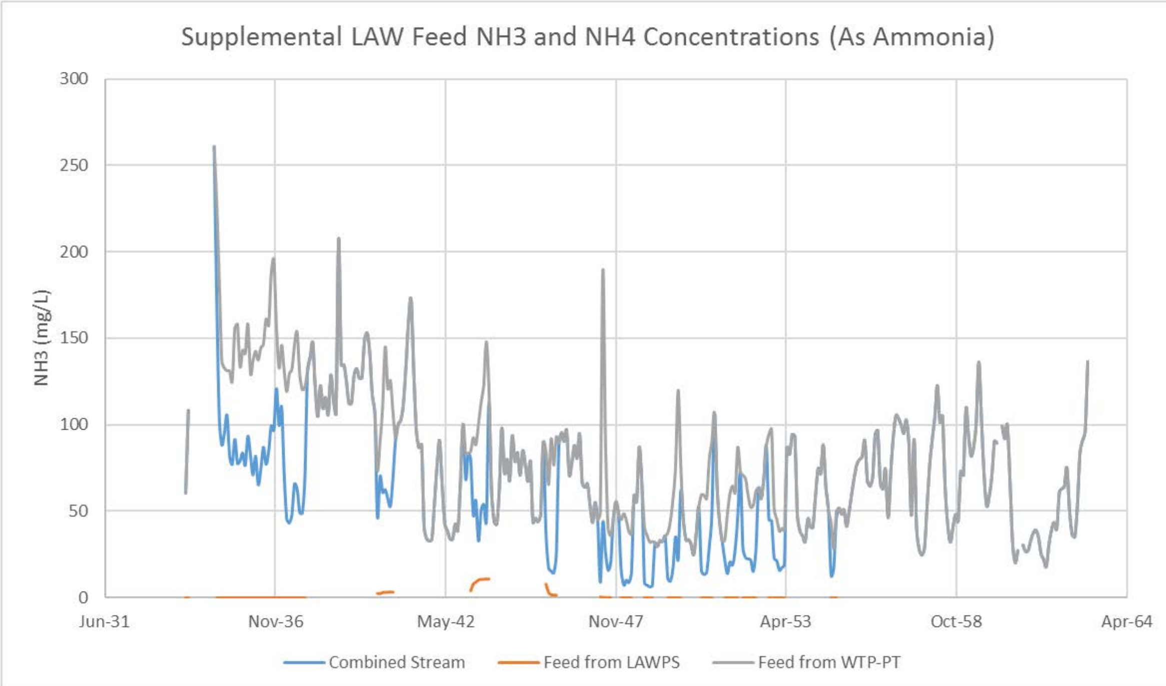

Figure K-5. Ammonia Concentration

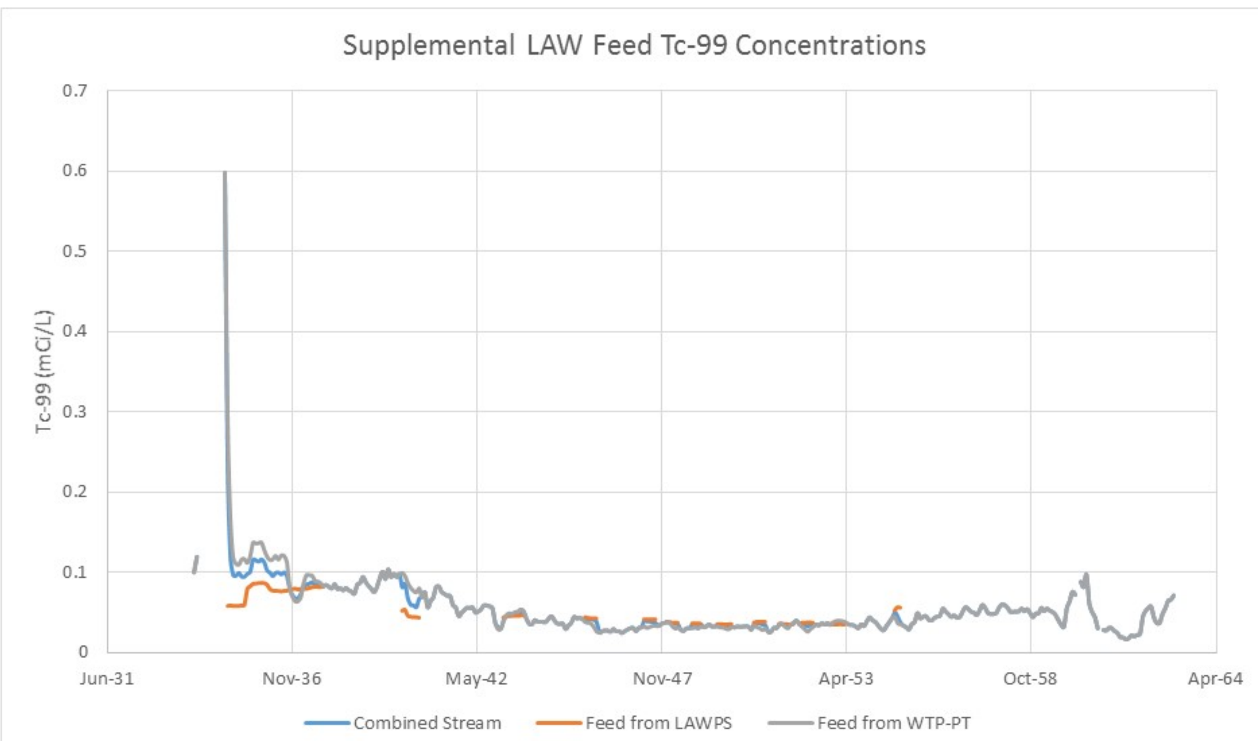

Figure K-6. Tc-99 Concentrations

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 K-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.

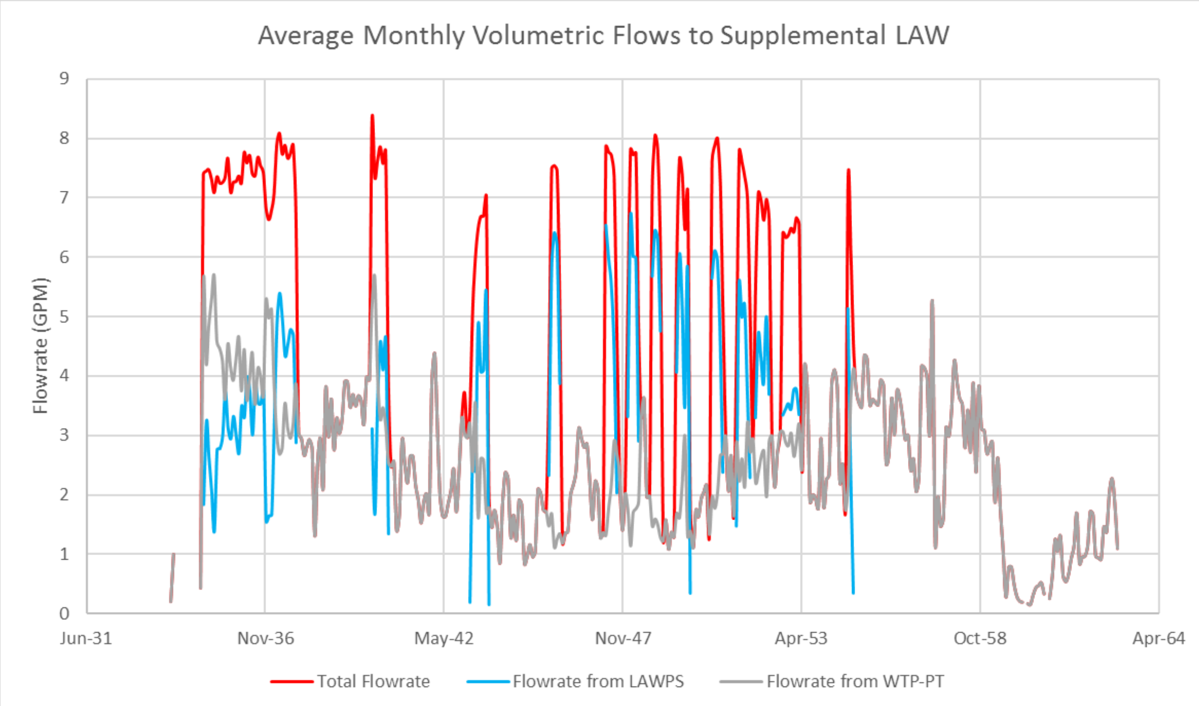

Figure K-7. Supplemental LAW Feed Volumes

K.3.1 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 document[10] which lists the calculational techniques and assumptions made in the calculations for each unit operation.

The TOPSim model has a number of simplifications that allow the entire Hanford waste disposition flowsheet to be modeled in a timely manner. These simplifications include, but are not limited to:

- single parameter "split factors" to determine partitioning of most species through each unit operation including the melter and melter offgas system
- lack of inclusion of the impact of melter idling on emissions from the melter
- 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 (^{129}I, ^{99}Tc, S, Cl, F, e.g.) in the feed to Supplemental LAW[11]. The single parameter split factors do not account for any process variation from changing feed compositions, but it is not possible to determine if the impact of this simplification would be conservative or non-conservative. The lack of flush water additions in WTP in the model primarily reduces the estimated amounts of secondary waste generated from LAW and 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.

K.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.

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.