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It is important for readers to understand that much of what is presented in these working draft documents has not been peer reviewed and is not intended to imply any final conclusions or represent a complete analysis. Peer reviews and subsequent revision and refinement will be completed during the spring and summer of 2018. 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).

Slides will be presented at the NAS Public Meeting #2 in Richland, WA on February 28 and March 1, 2018. These slides provide an overview of the working draft information included in the documents described above. The slides also have not undergone technical peer review and are considered working drafts on the subject matter presented.

Bill Bates

FFRDC Team Lead

Description of Baseline Process for LAW Immobilization and Supplemental LAW Immobilization at the Hanford Site

Summary

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 Hanford Waste Treatment and Immobilization Plant (WTP) LAW facility is exceeded. The excess supernate is generated because the amount of LAW supernate needed to transfer High Level Waste (HLW) to 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 is adjusted to not exceed the LAW capacity, then HLW processing will be reduced and the overall mission length would be extended.

The Supplemental LAW facility is expected to receive feed from two sources: Low Activity Waste Pretreatment System (LAWPS) and the WTP PreTreatment Facility (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.

The feed vector as defined in the Integrated Flowsheet will be used to evaluate the feasibility of immobilization technologies and to determine the scale of the facilities during cost estimation.

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Acronyms

HLW	High Level Waste
IDF	Integrated Disposal Facility
LAW	Low Activity Waste
LAWPS	Low Activity Waste Pretreatment Facility
LDR	Land Disposal Restrictions
LERF/ETF	Liquid Effluent Retention Facility / Effluent Treatment Facility
PT	PreTreatment Facility
PUREX	Plutonium Uranium Extraction
REDOX	REDuction and OXidation
WTP	Hanford Waste Treatment and Immobilization Plant

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[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].

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 1.

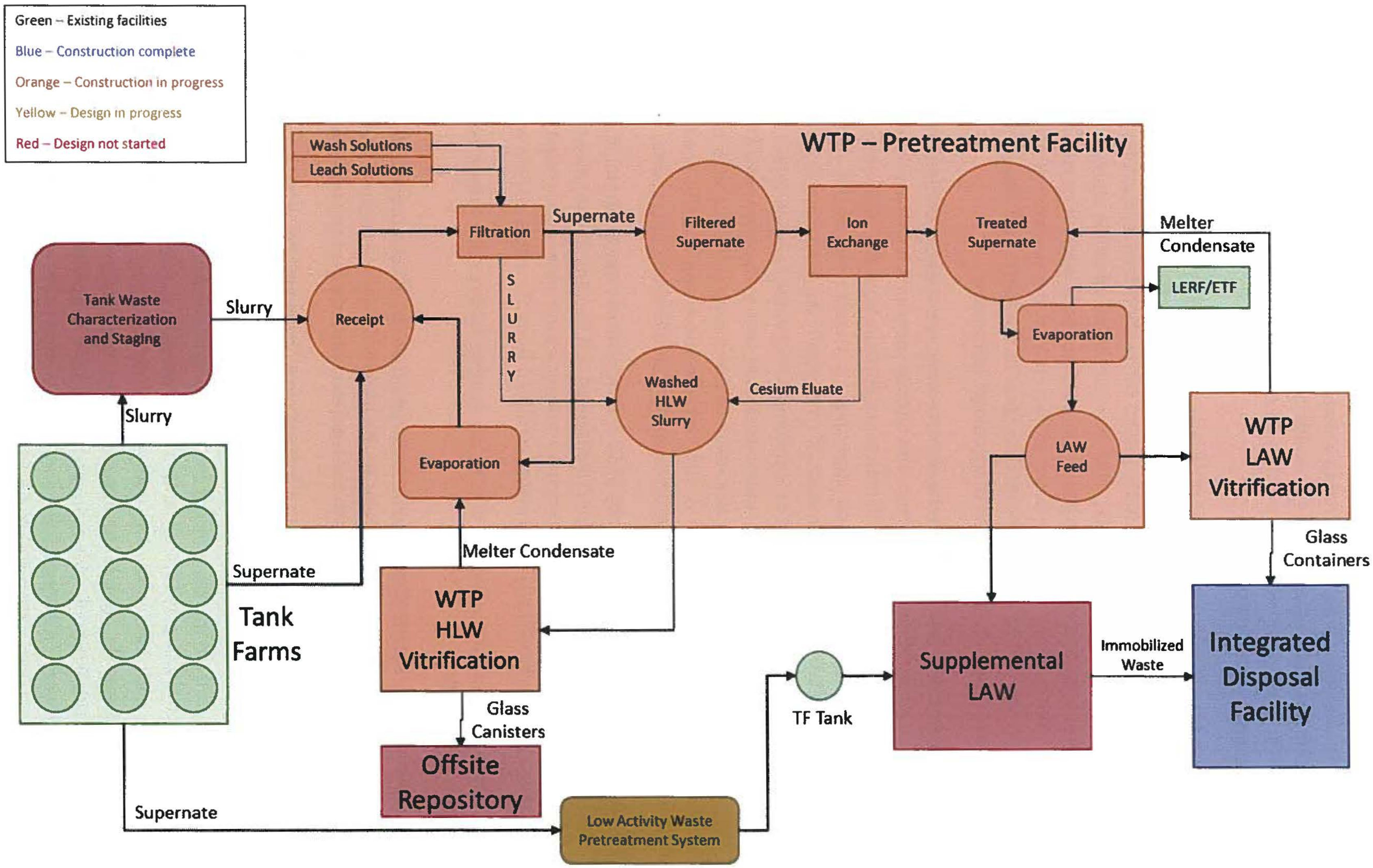

Figure 1. Simplified Flowsheet for Immobilization of Hanford Waste during Full WTP Operation as Defined in One System Integrated Flowsheet

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. Condensate from evaporation processes is sent to the Liquid Effluent Retention Facility / Effluent Treatment Facility (LERF/ETF) (only shown for treated feed evaporator). 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 half 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.

Solid secondary waste (spent air filters, etc.) is sent to an existing facility (LDR Treatment facility) for treatment to allow disposal at IDF.

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.

It should be noted that the recycle of LAW condensate results in a "flywheel" for semi-volatile species in the LAW vitrification system. A flywheel is defined as a closed process loop where only a portion of a species is retained in the products from the loop, as shown in Figure 2 for a species with a single pass retention of 33%. If the semi-volatile species is nearly completely removed from the exhaust by the offgas system, the only purge point is the glass. With only 33% retained in a single pass, the flywheel will concentrate the component until the feed to the melter is 3X the incoming concentration. Idling the melter will allow the semi-volatile species to vaporize from the molten glass, exacerbating the accumulation of material in the flywheel. When Supplemental LAW is operating, the "Blend" contents shown in Figure 2 are split between LAW vitrification and Supplemental LAW. If vitrification with a similar strategy to recycle the condensate is utilized for Supplemental LAW, a similar flywheel will exist internal to Supplemental LAW.

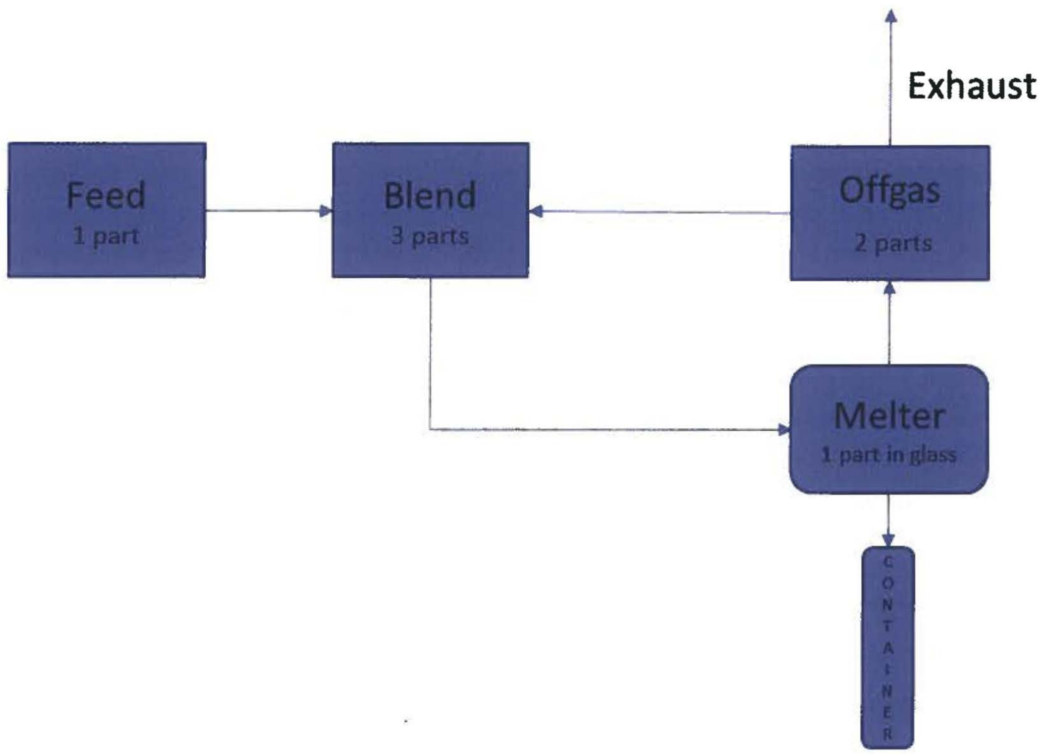

Figure 2. LAW Melter Recycle Flywheel

Direct Feed Options

The LAWPS facility is expected to start operation prior to PT and will feed LAW vitrification until PT is started. Supernate from the tank farm will be sent to LAWPS with the treated supernate stored in a tank farm tank until being sent to WTP LAW vitrification for immobilization. Melter condensate will be handled by the Effluent Management Facility (not shown in Figure 1) during direct feeding of the WTP LAW vitrification facility 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]. The direct feed option for LAW is utilized during full operation to supply additional feed to the Supplemental LAW facility from LAWPS. Direct feeding options for HLW would change the assumptions for feed to PT and could change the amount of feed processed through Supplemental LAW by creating additional LAW from the added HLW processing or by replacement of the processing of HLW through PT which would change the amount and composition of LAW utilized and generated during HLW operations.

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 WTP LAW vitrification facility is met. Preliminary estimates for immobilized waste volume are performed in the Integrated Flowsheet for both the vitrification and grout options. Steam reforming and other alternatives to vitrification are not considered as options in the Integrated Flowsheet.

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 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 Integrated Flowsheet model contains a 500,000 gallon lag storage tank at the front end of the Supplemental LAW process to receive feed from LAWPS and PT. The amount of lag storage between the facilities is not finalized, but is assumed to be part of the Supplemental LAW facility. It is noted that LAWPS will utilize an existing tank farm tank as lag storage between LAWPS and the WTP LAW vitrification facility during direct feed operations; this same tank could continue to perform that function after startup of Supplemental LAW and could be utilized as the lag storage vessel for all feeds to be sent to Supplemental LAW.

The interfaces between Supplemental LAW and other facilities are described in Table 1 and shown in Figure 3, 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 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

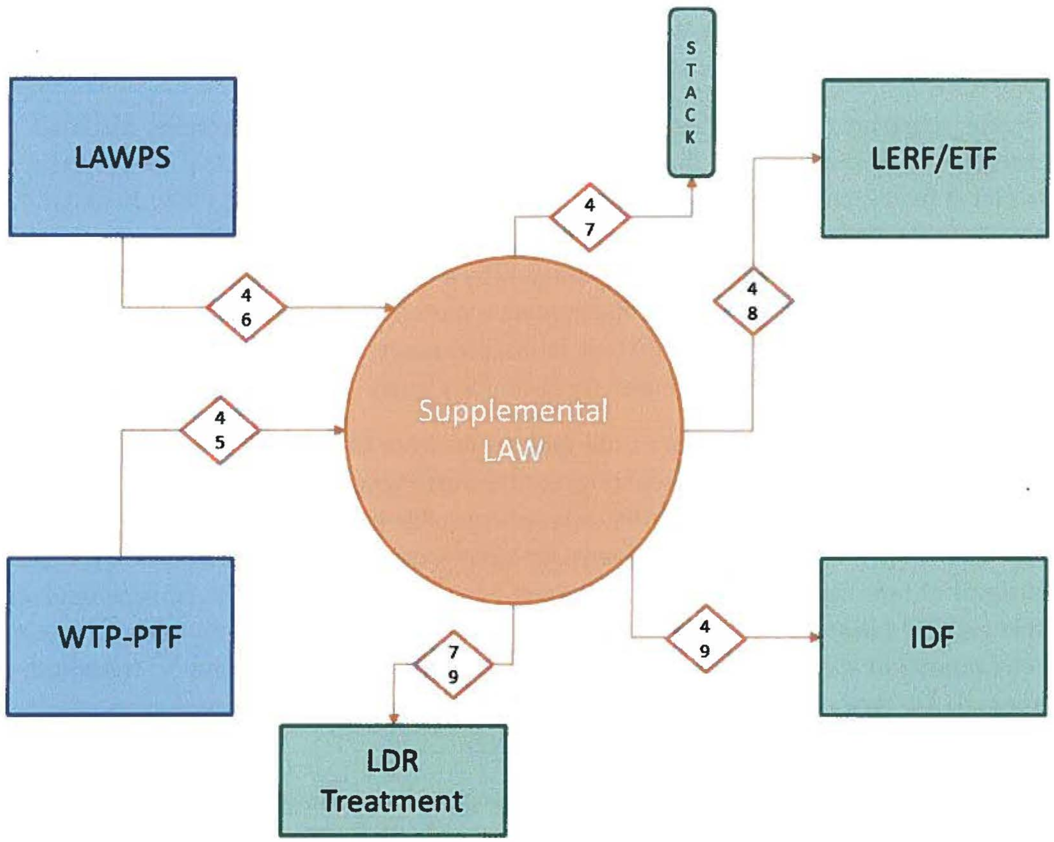

Figure 3. Supplemental LAW Detail: Interfaces

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 generate containers of immobilized LAW waste is the assumed baseline technology with disposal at the IDF. Bulk vitrification, grout, and steam reforming have been evaluated in the past for LAW immobilization and will be evaluated during this review as alternatives to Supplemental LAW vitrification. Additional options being considered during this review are to dispose the immobilized LAW at an offsite, commercial facility. Offsite disposal could include 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 (i.e. the waste would be blended as needed to meet the specified limits for Supplemental LAW).

Feed Vector

The Supplemental LAW feed vector [7] calculated for the One System River Protection Project Integrated Flowsheet [6] will be 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. Past reviews of Supplemental LAW did generate some information on the feed vector to Supplemental LAW, but changes to the projected flowsheet have made these past projections obsolete[8,9]. 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 feed vector is based on compositions of the tank waste from the Best Basis Inventory (BBI). The uncertainty of the data in the BBI varies depending on the waste type as well as the number and type of samples taken from each tank[10]. In addition, the assumptions made during flowsheet model run (including tank farm retrieval sequencing, selection of feeds for LAWPS processing, etc.) significantly impact the results. Retrieval of tank waste at the Savannah River Site has shown that tank compositions can be different than expected based on processing history and past samples and that the retrieval sequencing will change frequently to allow retrievals to keep up with required production rates[11]. Therefore, while the Supplemental LAW feed vector is the best currently data available, the actual waste processed through Supplemental LAW could be 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 4, Figure 5, Figure 6, and Figure 7. Thus, any Supplemental LAW process would have to accommodate the expected extremes in waste feed compositions unless sufficient lag storage is provided to smooth these peaks or the retrieval plan for tank waste is changed to blend the wastes as needed to eliminate the 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 Supplemental LAW vitrification facility[6] from PT in the Integrated Flowsheet.

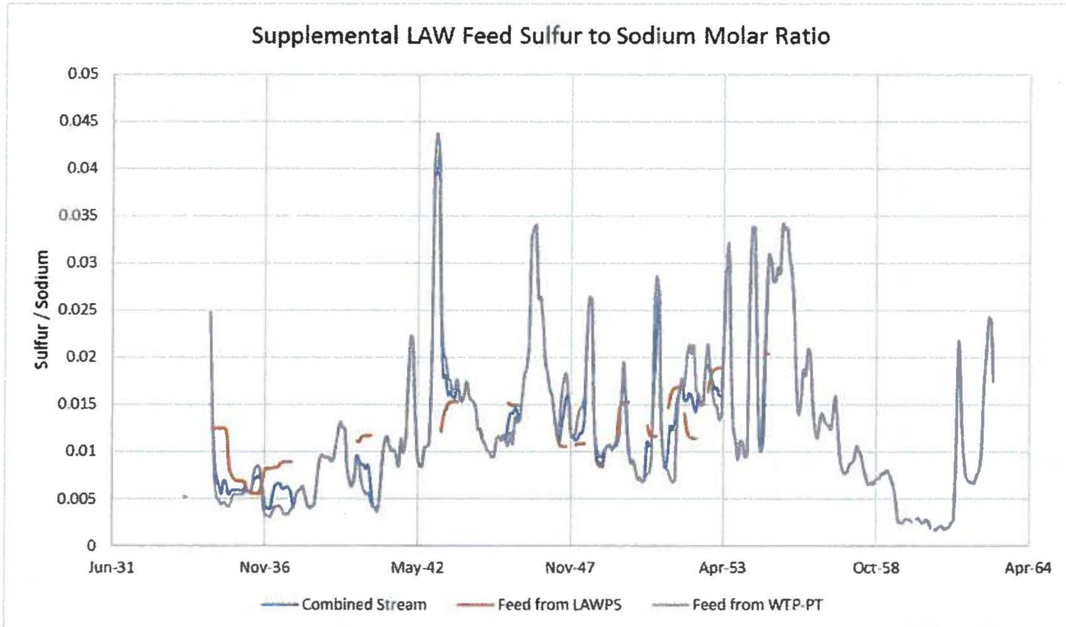

Figure 4. Sulfur to Sodium Ratio

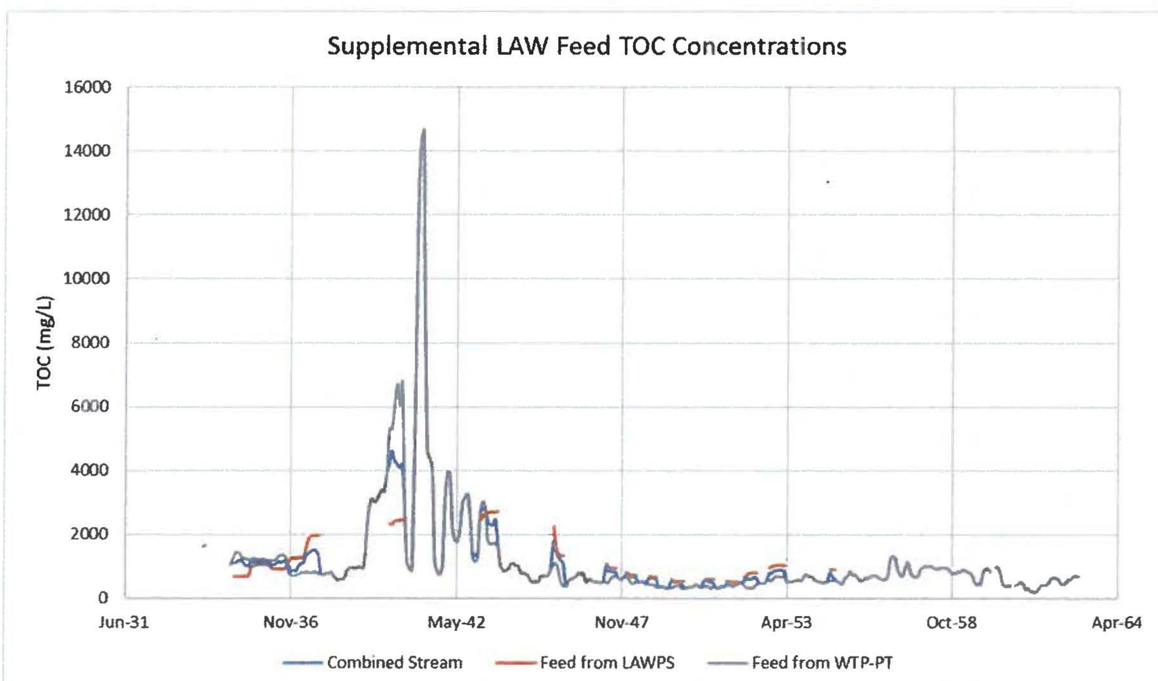

Figure 5. TOC Concentration

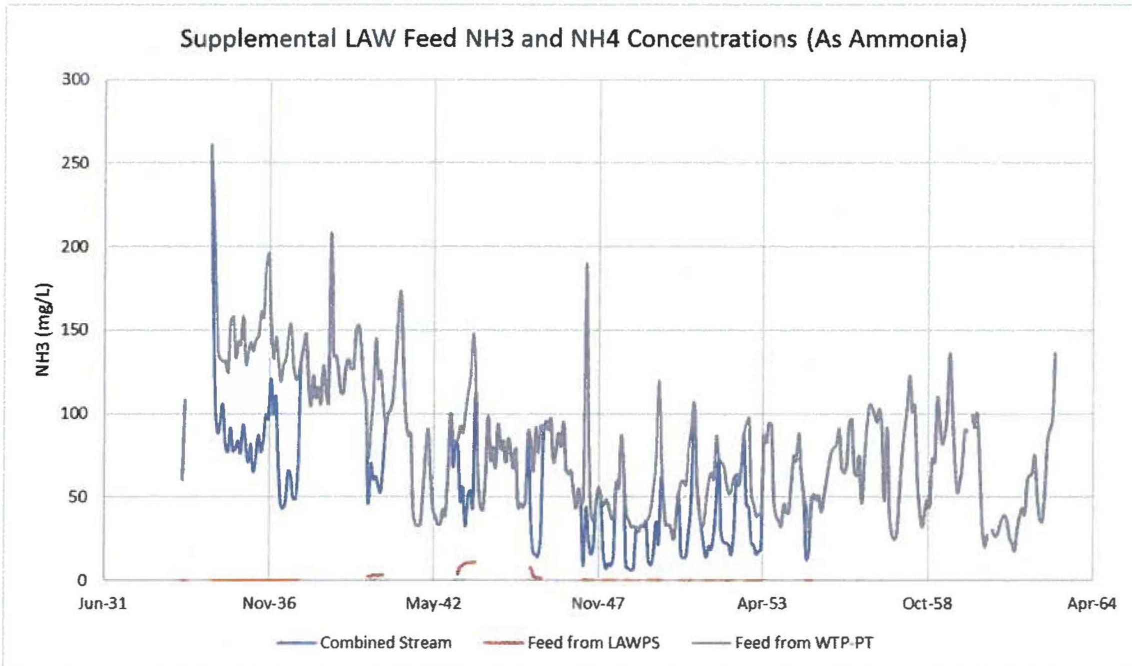

Figure 6. Ammonia Concentration

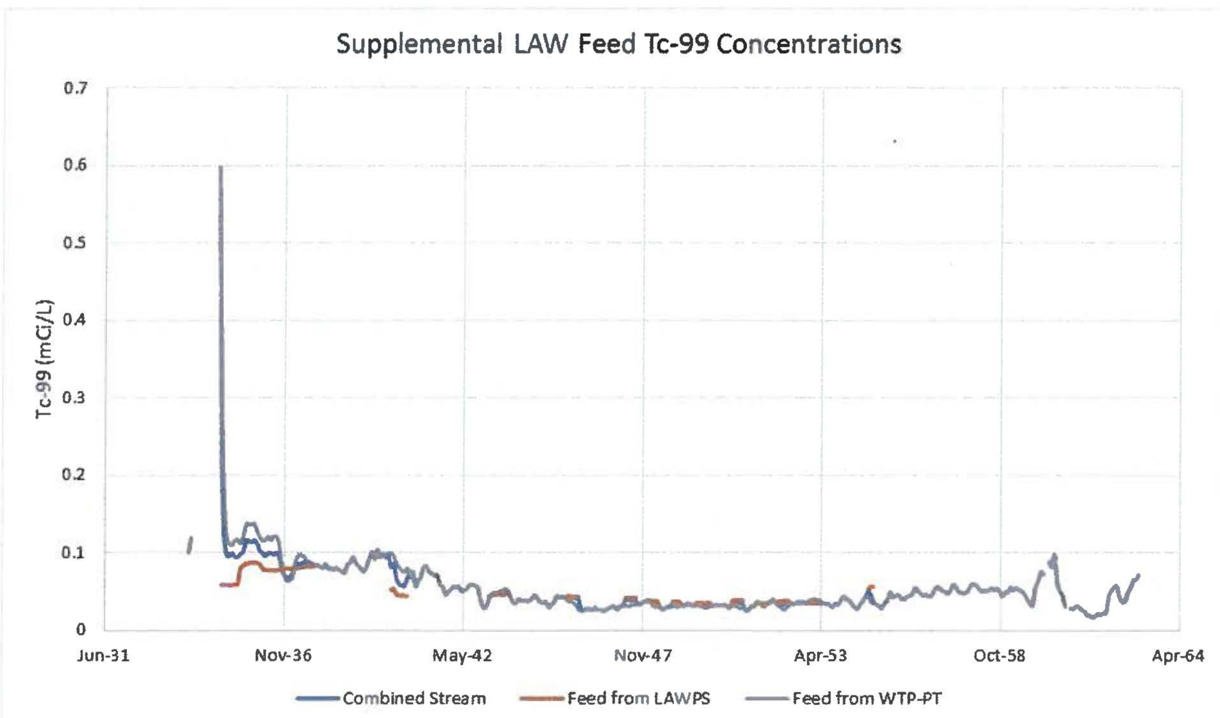

Figure 7. Tc-99 Concentrations

In addition, as a result of the unconstrained model and the desire to achieve full capacity through the HLW vitrification facility, the Supplemental LAW could also need to accommodate extremes in feed volume, as shown in Figure 8. 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.

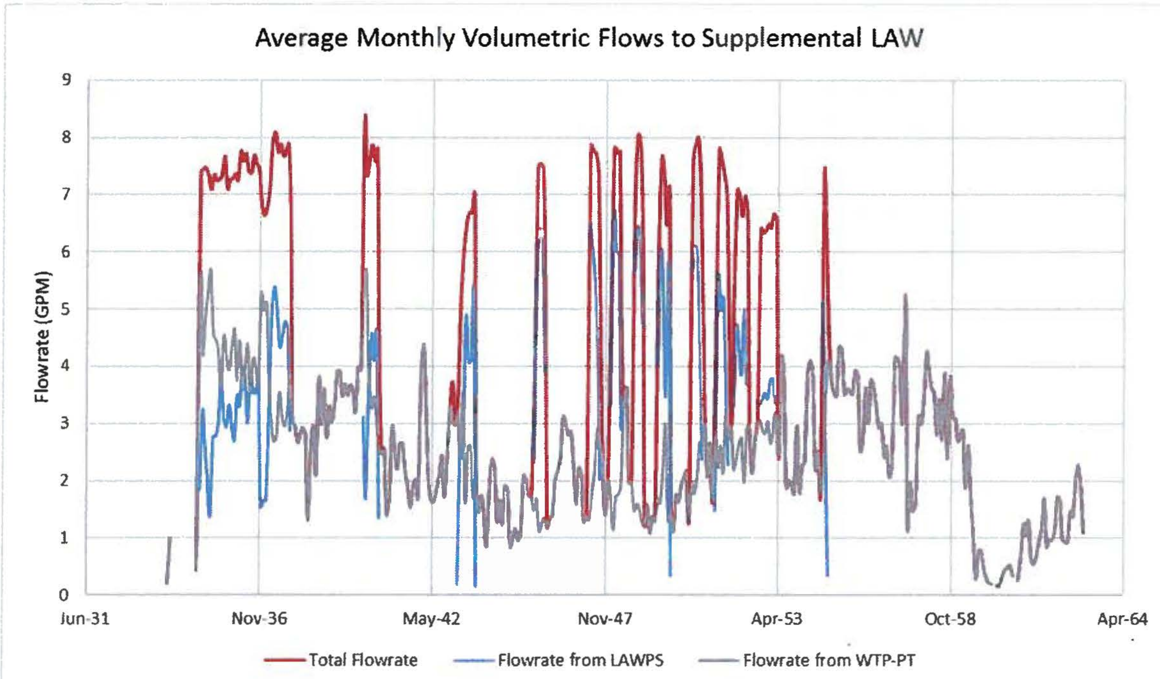

Figure 8. Supplemental LAW Feed Volumes

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[12] 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 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[13] since recycle from the WTP LAW facility is part of the feed to Supplemental LAW. Frequent idling could result in a feedback mechanism that results in most of the ^{129}I and ^{99}Tc being sent to Supplemental LAW with very little of either species retained in the glass containers from LAW vitrification.

The single parameter split factors do not account for any process variation from changing feed compositions, therefore the composition of the recycle streams returned to the LAW feed from WTP LAW vitrification contains uncertainty from the use of these split factors. 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. Changes in the retrieval sequence and timing should be expected during processing, therefore the feed vector should not be expected to be exactly as shown in the current system planning.

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. If a small number of peaks are noted outside the feasibility of the immobilization technology, an engineering evaluation will be performed to determine whether the peaks could be eliminated by additional lag storage or by a different blending strategy during retrievals.

Conclusions

The feed vector developed for the Integrated Flowsheet[7] 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.

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13. 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.

NDAA 3134 Supplemental LAW Treatment Alternatives Analysis Approach

The FFRDC Team (Team) established a Program Plan that defined, at a high-level the analysis approach – considering the "...ability of supplemental treatment alternatives to meet the waste acceptance criteria of potential disposal sites, ... their major risks, regulatory impacts, and costs and schedules."[1] To conduct the analysis, the Team considered lessons learned from recent DOE alternatives analysis activities, including DOE guidance on conduct of "Assessment of Alternatives (AOAs)"[2], and GAO recommendations for best practices in alternatives assessments.[3] A structured approach to the analysis was selected and lines of inquiry (LOIs) were established. These LOIs represent the key areas of evaluation, with corresponding assessment criteria and a pre-established set of qualitative metrics (see Table 1).

Risk Assessment as it Relates to the NDAA 3134 Supplemental Treatment Study

Risk Assessment is the application of a systematic process for evaluating the potential risks involved in a project activity or enterprise. The NDAA 3134 Supplemental Treatment Study will assess potential risks as part of its evaluation of supplemental treatment technology alternatives. However, there are many aspects of risk that could be evaluated. This section describes the risks being considered within the FFRDC scope of the NDAA study, and the approach being used to assess those risks, either qualitatively or quantitatively.

Background: Risk assessment techniques can be applied at many different levels, and the term has different connotations when used in different risk domains, using different analysis methods, and used for different applications. The principle alternative risk domains where risk assessment is applied include project risk, environmental risk, and safety risk. 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."[4] 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. EPA defines environmental 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.[5] 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

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[1] SRNL. 2017. Program Plan for Analysis of Approaches for Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation. SRNL-RP-2017-00242. Savannah River National Laboratory. Aiken, South Carolina.

[2] DOE. 2016. Program and Project Management for the Acquisition of Capital Assets. DOE O 413.3B. U.S. Department of Energy, Washington D.C. Appendix C of DOE O 413.3B defines requirements for Assessment of Alternatives.

[3] GAO. 2014. DOE and NNSA Project Management – Analysis of Alternatives Could Be Improved by Incorporating Best Practices. GAO-15-37. U.S. Government Accountability Office, Washington D.C.

[4] Project Management Institute, *A Guide to the Project Management Body of Knowledge – Fifth Edition*, Project Management Institute Inc., 2013.

[5] "About Risk Assessment." *Risk Assessment*. U.S. Environmental Protection Agency, 1 May 2017, Web. 17 January 2018.

performance assessment analysis required to operate and maintain DOE LLW disposal facilities.[6] OSHA defines safety risk as the product of hazard and exposure in the context of workplace injuries, illnesses, and incidents, while NRC's concept of risk "...combines the probability of accident with the consequences of that accident,"[7] and they use risk information associated with nuclear reactors and nuclear materials to reduce the probability of an accident as well as mitigate its consequences.

Several alternative risk assessment methods are applied in each of the risk domains described above, including probabilistic risk assessment (PRA), semi-quantitative risk assessment, and qualitative hazards analysis. PRA is a method commonly applied by NRC for nuclear applications to estimate risk "by computing real numbers to determine what can go wrong, how likely is it, and what are its consequences." PRA in the nuclear application is typically used to "provide insight into the strengths and weaknesses of the design and operation of a nuclear power plant" or facility,[7] and usually involves a very structured, systematic, and quantitative analysis explicitly accounting for uncertainties through probabilistic methods. Semi-quantitative risk assessment methods provide an intermediate level between a fully quantitative risk assessment (i.e., with numbers, such as a PRA), and a more textual evaluation or qualitative risk assessment. Semi-quantitative methods provide a structured approach to ranking risks with numeric scores, frequently using expert input versus mathematical models. Qualitative risk or hazards assessments methods produce non-numerical estimates of risk, and may use a risk matrix to organize levels of impact and likelihood, and prioritize or rank risks for future action.

Each of the three risk assessment methods described above are applied in each of the different domains, and in several different application areas, including alternatives analysis, risk acceptance analysis, and cost-benefit analysis. The NDAA 3134 scope is considered by the Team as principally an alternatives analysis focused on comparing a number of different approaches to achieve a common objective, and assessing the relative merits and risks associated with each alternative. 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."[3]

The FFRDC team (Team) is identifying and evaluating risks in each of the primary domains of project, environment, and safety risks, and using semi-quantitative methods applied to an alternatives analysis application. Specifically, for each primary alternative being evaluated, the team is applying an assessment methodology that includes identifying and documenting 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 is assessing the potential for compliance with disposal site environmental performance objectives. Specific approaches being applied to each of these assessment activities are described below.

[6] "LFRG DOE Order 435.1." *Office of Environmental Management*. U.S. Department of Energy, Undated, Web. 17 January 2018.

[7] NRC. 2018. "Risk Assessment in Regulation." Risk Assessment. U.S. Nuclear Regulatory Agency, 4 January 2018, Web. 8 February 2018.

Assessment Methodology

The LOIs, criteria, and semi-quantitative metrics selected for the assessment are outlined in Table 1. The primary LOIs are represented by the column headers, the criteria are represented by the first row of the table shaded green, and the metrics for each criterion are represented in the unshaded bottom two rows. For each technology and its corresponding flowsheet, once narrowed to a finite list of options/alternatives for consideration, the Team will be evaluating each option against the predefined LOIs. Expert elicitation, supported by technical documentation and analysis, will be used to semi-quantitatively evaluate each alternative option. The subject matter experts (SMEs) used in this elicitation will be comprised of the FFRDC team members. Supporting documentation will be provided by the SMEs, as well as additional reach back to SMEs from the FFRDCs, Industry, and broader DOE community, as appropriate. Elicitation input will be collected within decision analysis software (e.g., Expert Choice) to support thorough Team interrogation, discussion, and sensitivity analysis.

An SME in risk analysis will support the development and implementation of the expert elicitation process to assure that risks are being appropriately considered. 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 in project-, operational execution-, and technology maturation-risks. 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 handling 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. Risks will be considered for each LOI in the development and implementation of the evaluation to assure that important risks are not overlooked. Assumptions and considerations in the evaluation of each alternative will be documented, highlighting potential risks identified for each alternative specific to each criterion, where appropriate.

Disposal Environmental Risk Assessment: Onsite (Hanford) and commercial offsite (e.g., WCS) disposal is being 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.[8]

[8] Mann, FM, RJ Puigh, R Khaleel, S Finfrock, BP McGrail, DH Bacon, and RJ Serne. 2003. Risk Assessment Supporting the Decision on the Initial Selection of Supplemental ILAW Technologies. RPP-17675 Rev. 0, CH2M HILL Hanford Group, Inc., Richland, Washington.

The approach proposed for this assessment (aka Risk Assessment, or Mini-PA) will include:

- 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 2003 Risk Assessment, 2014 EIS, and the 2017 IDF Performance Assessment will be provided, along with a discussion of any differences in assumptions or input parameters used by the Study Team.
- Each waste form will be 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 will be considered to assess the uncertainty in CoC release rates from the disposal facility (e.g., range of values).
- Groundwater impacts have been previously shown to be a primary area of concern relative to assessment of primary and secondary waste form disposal in IDF. Contaminant transport from the IDF to the groundwater and downgradient point of compliance is driven principally by the release rate from the IDF, and is assumed 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, will be used to quantitatively translate IDF release rate to the potential environmental impacts to groundwater and human receptors (e.g., groundwater concentration and dose).

Table 1. NDAA 3134 FRRDC Supplemental LAW Options and Areas of Consideration

<u>OPTIONS</u> **Pre-Treatment Waste, Disposition Technology, & Disposal Location**	**TRL & Complexity**	**Safety**	**Robust Operational Flexibility (ability to handle wide variety of waste feed streams)**	**Cost LC & Annual**	**Schedule**	**Risks and Opportunities**	**Waste form Performance**	**Secondary Wastes**	**Regulatory Considerations (Includes waste form & packaging)**			**End State Decommissioning**
									Processing	**Shipment**	**Disposal**	
- Option Description - High Level Flowsheet a. Sub-option 1 b. Sub-option 2 c.	- TRL - Review prior documents assessing TRL - Assess qualitatively as a team - Use EM TRL guide - Complexity - Number of unit ops - Type unit ops - Secondary wastes generated (minimal, moderate, high) - Difficulty handling off-spec waste products - Major equipment replacement challenges (i.e. melters, etc.)	- Nuclear Safety - Chemical Safety - Accident/Hazard Analysis - Number of Hazards requiring controls (evaluate qualitatively, focus on active controls) - Address - Pretreatment - Immobilization - Packaging - Transport - Disposal	- Number of challenging feed streams or constituents - Impact to Pretreatment Needs - Fraction of feed streams not compatible	- Project Cost - Operations Cost - Annual Cost - Pedigree & method/reference for estimate - Comparison to "baseline" EM liability cost profile - Include Disposal & Transport Costs - Use Net Present Value or consistent "Dollars"	- Comparison to "baseline" - Options for Acceleration	- Project Risks - Operational Execution Risks - TRL related risks with technology maturation - Opportunities to accelerate schedule or reduce LC cost	- Comparison to Disposal Site WACs - Physical Performance Summary - Max Release Rate per radionuclide - TCLP Leaching - Compressive Strength - Rad Tolerance - Thermal Tolerance - Other	- Quantity - Contribution to the Environment Assessment (EA) - Disposal Pathways - Evaluation against LAW criteria	- NEPA - Long Term Environmental Impacts - Env. Permits	- DOT & NRC shipping compliance - Road vs. Rail considerations - Onsite shipping compliance - NEPA - Long Term Environmental Impacts - Env. Permits - Address concentration (Ci/cm^3) - Total volume - Inventory per container	- NEPA - Long Term Environmental Impacts - Env. Permits - Address concentration (Ci/cm^3) - Total volume - Inventory per container - PA compliance	- Decon - Removal - Entombment
	5 = TRL is judged to be 6 or greater 3 = TRL is judged to be 4 or 5 1 = TRL is judged to be 3 or less	5 = Few, if any, hazards require controls; few controls are active controls 3 = Moderate hazards require controls; moderate number of controls are active controls 1 = Significant active controls or new hazards	5 = High confidence that requirements for downstream processing and disposition will be consistently met 3 = Moderate confidence that requirements for downstream processing and disposition will be consistently met 1 = Low confidence that requirements for downstream processing and disposition will be consistently met	5 = Estimated cost is low relative to other alternatives; uncertainty in cost estimate is low 3 = Estimated cost is moderate relative to other alternatives uncertainty in cost estimate is moderate 1 = Estimated cost is high relative to other alternatives; uncertainty in cost estimate is high	5 = Estimated time to complete the mission is short relative to other alternatives; Confidence in schedule estimate is high 3 = Estimated time to complete the mission is moderate relative to other alternatives; Confidence in schedule estimate is moderate 1 = Estimated time to complete the mission is long relative to other alternatives; Confidence in schedule est. is low	5 = Risks low compared to other options 3 = Risks moderate compared to other options 1 = Risks high compared to other options	5 = Waste form meets pertinent criteria 3 = Some aspects of waste form may not meet criteria 1 = Waste form unlikely to meet criteria	5 = No new processes needed 3 = Planned processes will be challenged 1 = New processes will be needed	5 = High confidence that alternative meets existing waste form regulations; or regulations can be modified so that alternative satisfies regulations 3 = Moderate confidence that alternative meets waste form regulations; or regulations can be modified so that alternative satisfies regulations 1 = Low confidence that alternative meets waste form regulations; or regulations can be modified so that alternative satisfies regulations	5 = High confidence that alternative meets existing waste form regulations; or regulations can be modified so that alternative satisfies regulations 3 = Moderate confidence that alternative meets waste form regulations; or regulations can be modified so that alternative satisfies regulations 1 = Low confidence that alternative meets waste form regulations; or regulations can be modified so that alternative satisfies regulations	5 = High confidence that alternative meets existing waste form regulations; or regulations can be modified so that alternative satisfies regulations 3 = Moderate confidence that alternative meets waste form regulations; or regulations can be modified so that alternative satisfies regulations 1 = Low confidence that alternative meets waste form regulations; or regulations can be modified so that alternative satisfies regulations	5 = Estimated cost is low relative to other alternatives; uncertainty in cost estimate is low 3 = Estimated cost is moderate relative to other alternatives uncertainty in cost estimate is moderate 1 = Estimated cost is high relative to other alternatives; uncertainty in cost estimate is high

Table 1. (continued)

OPTIONS Pre-Treatment Waste, Disposition Technology, & Disposal Location	TRL & Complexity	Safety	Robust Operational Flexibility (ability to handle wide variety of waste feed streams)	Cost LC & Annual	Schedule	Risks and Opportunities	Waste form Performance	Secondary Wastes	Regulatory Considerations (Includes waste form & packaging)			End State Decommissions
									Processing	Shipment	Disposal	
	5 = Technology can be readily matured to TRL 6 within schedule and budget constraints 3 = Technology can be matured to TRL 6, but not within schedule and budget constraints 1 = Unlikely that technology can achieve TRL 6 within an acceptable timeframe/cost		5 = Requires no pre-treatment of unique waste feed streams 3 = Requires some pre-treatment of unique waste feed streams 1 = Requires extensive pre-treatment of unique waste feed streams	5 = High confidence that alternative can be executed within planning profile (under peak) 3 = Moderate confidence that alternative can be executed within planning profile (under peak) 1 = Low confidence that alternative can be executed within planning profile (under peak)								
	5 = Low number of unit operations and low complexity in unit operations; easy to address off-spec product 3 = Moderate number of unit operations and moderately complex unit operations; moderately difficult to address off-spec product 1 = High number of unit operations and highly complex unit operations; very difficult to address off-spec product											
	5 = Simple start-up/shutdown operations; operator interaction with system is minimal 3 = Moderate start-up/shutdown operations; operator interaction with system is moderate 1 = Complex start-up/shutdown operations; operator interactions with system is extensive											

Approach to Assessment of "Other" Technologies
NDAA 3134 Supplemental LAW Treatment

Section 3134 of the NDAA for 2017 specified elements of the FFRDC study to include:

> *"(1) An analysis of, at a minimum, the following approaches for treating the low-activity waste described in subsection (a):*
> *(A) Further processing of the low-activity waste to remove long-lived radioactive constituents, particularly technetium-99 and iodine-129, for immobilization with high-level waste.*
> *(B) Vitrification, grouting, and steam reforming, and other alternative approaches identified by the Department of Energy for immobilizing the low-activity waste."*

A primary focus of the study scope is on the three immobilization approaches—vitrification, grouting, and steam reforming—outlined in subsection (1)(B) that were considered in the 2003 supplemental treatment evaluation process (Raymond et al., 2004) and subsequent Tank Closure and Waste Management Environmental Impact Statement (TCWM EIS, DOE, 2014). However, the FFRDC Team (Team) is also evaluating approaches for further processing to remove certain radionuclides and chemical constituents, as well as other alternative approaches consistent with the underlined elements of (1)(A) and (1)(B). This paper describes the approach and methodology being applied to consideration of additional processing and alternative approaches.

Methodology for Identification and Analysis of Processing Alternatives

DOE and its contractors evaluated a wide range of options for accelerating the tank waste treatment mission as part of the initial supplemental treatment assessment process in the early 2000's (Choho and Gasper, 2002), and many of these are also described in the TCWM EIS. Subsequently, several alternative processing options have been further researched and evaluated. Therefore, the Team's approach to identifying processing alternatives is focused first on consideration of those options previously considered. The methodology for identification and assessment includes:

1. Identifying options previously considered as part of the supplemental treatment selection process
2. Reviewing the prior rationale for the options' earlier disposition (e.g., screened out, or further consideration recommended),
3. Assessing any further development or evaluation of the technology option since its previous evaluation.
4. Evaluating the current relevance of the option to the scope of the review, potential benefits to the supplemental treatment mission, and likelihood that those benefits could be realized if pursued.
5. Documenting the assessment and recommendations for each option considered.

Methodology for Identification and Analysis of Further Processing Approaches

Further processing of the low-activity waste stream prior to immobilization may provide benefits by addressing potential limitations in processing of the waste into a stable waste form, improving disposal performance, or meeting other regulatory requirements. The NDAA Section 3134 specifically requested consideration of Tc-99 and I-129 separations. However, other separations options may also provide potential benefits. Therefore, the Team's approach to identifying further processing approaches is focused on an assessment of each immobilization alternative, and identification of any processing, disposal, or regulatory compliance limitations that could be potentially mitigated by further processing. The Team also considered opportunities to improve options for processing or disposal (e.g., cost or risk reduction) through further processing. Specifically, the methodology for identification and assessment includes:

1. Identifying potential limitations of each primary waste processing technology flowsheet (vitrification, grouting, steam reforming) in meeting regulatory requirements and/or improving waste form (i.e., disposal) performance.
2. Identifying potential areas of opportunity for each flowsheet, from waste processing through transportation and disposal, where further processing could provide substantial cost or risk reduction.
3. Assessing process performance requirements necessary to address the limitation or opportunity. For example, how much Tc-99 removal would be required to meet a disposal WAC or other performance requirement?
4. Identifying and evaluating further processing technologies and flowsheets that may have the potential to meet the process performance requirements.
6. Documenting the assessment and recommendations for each option considered.

Summary of Alternatives and Processing Approaches Under Review

A preliminary list of alternative and further processing approaches being reviewed or considered within the study are identified in Table 1. Implementation of the analysis methodologies identified above are currently in progress. Therefore, processing options identified in Table 1 are incomplete. Options may be removed from consideration, and other options may be added as the analysis progresses.

Table 1. Preliminary Identification of "Other" Options for Review

Process Category	Technology Option	Key Attributes	Source
Immobilization	Vitrification with Phosphate Glass	Increased sulfate and chromium loading in glass, increased vitrification throughput	DOE, 2014
Immobilization	Active-metal reduction	Destroys nitrate and nitrites, produces a ceramic waste form	Choho and Gasper, 2002 Gasper et al 2002 DOE, 2014
Pretreatment	Fractional crystallization	Separate Cs, Tc, I from a high sodium fraction of the LAW	DOE, 2014 Herting, 2007
Pretreatment	Clean salt (with or without sulfate removal)	Separate a "clean" sodium (and optional sulfate) fraction for immobilization in ceramic, grout, or polymer	Choho and Gasper, 2002 Gasper et. al. 2002 DOE, 2014
Pretreatment	Plasma mass separator	Physical separation of elements by atomic mass to produce heavy and light fractions for treatment	DOE, 2014
Pretreatment	Caustic recycle	Electrochemical separation of sodium hydroxide for recycle, reducing LAW volume	DOE, 1999
Pretreatment	Technetium removal	Reduce Tc in LAW fraction or secondary waste	DOE, 2014
Pretreatment or Off-gas Treatment	Iodine removal	Reduce I in LAW fraction or secondary waste	DOE, 2014
Pretreatment	Strontium removal	Reduce soluble Sr-90 in specific LAW feeds	n/a[1]
Pretreatment	Treatment of RCRA LDR Constituents	Oxidation or reduction to destroy organics or reduce metal mobility in LAW waste form (e.g., grout)	n/a[1]

[1] NDAA 3134 FFRDC Team Assessment. Analysis of specific technology options in progress

References

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

DOE. 2014. Tank Closure and Waste Management Environmental Impact Statement. DOE/EIS-0391. U.S. Department of Energy, Washington D.C.

DOE. 1999. Innovative Technology Summary Report: Caustic Recycle. DOE/EM-0494. U.S. Department of Energy, Washington D.C.

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

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

Raymond RE, RW Powell, DW Hamilton, WA Kitchen, BM Mauss, TM Brouns. 2004. Initial Selection of Supplemental Treatment Technologies for Hanford's Low-Activity Tank Waste. RPP-19763-FP/WM-4525. CH2M HILL Hanford Group, Inc. Richland, Washington. *Presented at WM'04 Conference, February 29-March 4,2004, Tucson, AZ.*

5.2 VITRIFICATION

Two technologies will be evaluated for the vitrification of Supplemental Low Activity Waste (SLAW). The first vitrification facility evaluated will have similar attributes to the Waste Treatment and Immobilization Plant (WTP) LAW facility. The seconds technology is the Bulk Vitrification of low activity waste.

For the first technology, the SLAW will receive treated supernate from the WTP Pretreatment facility (PT) and the LAW Pretreatment System (LAWPS).[1] 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 slurried waste and GFCs into a vitrified waste form.[2] The GFCs are weighed and blended in a cold feed area per the recipe calculated from 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 a portion of the semi-volatiles components are partitioned to the melter offgas system.

The melter offgas system will condense the water and volatile components as well as remove entrained particulate from the offgas.[3] 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.[4] 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.

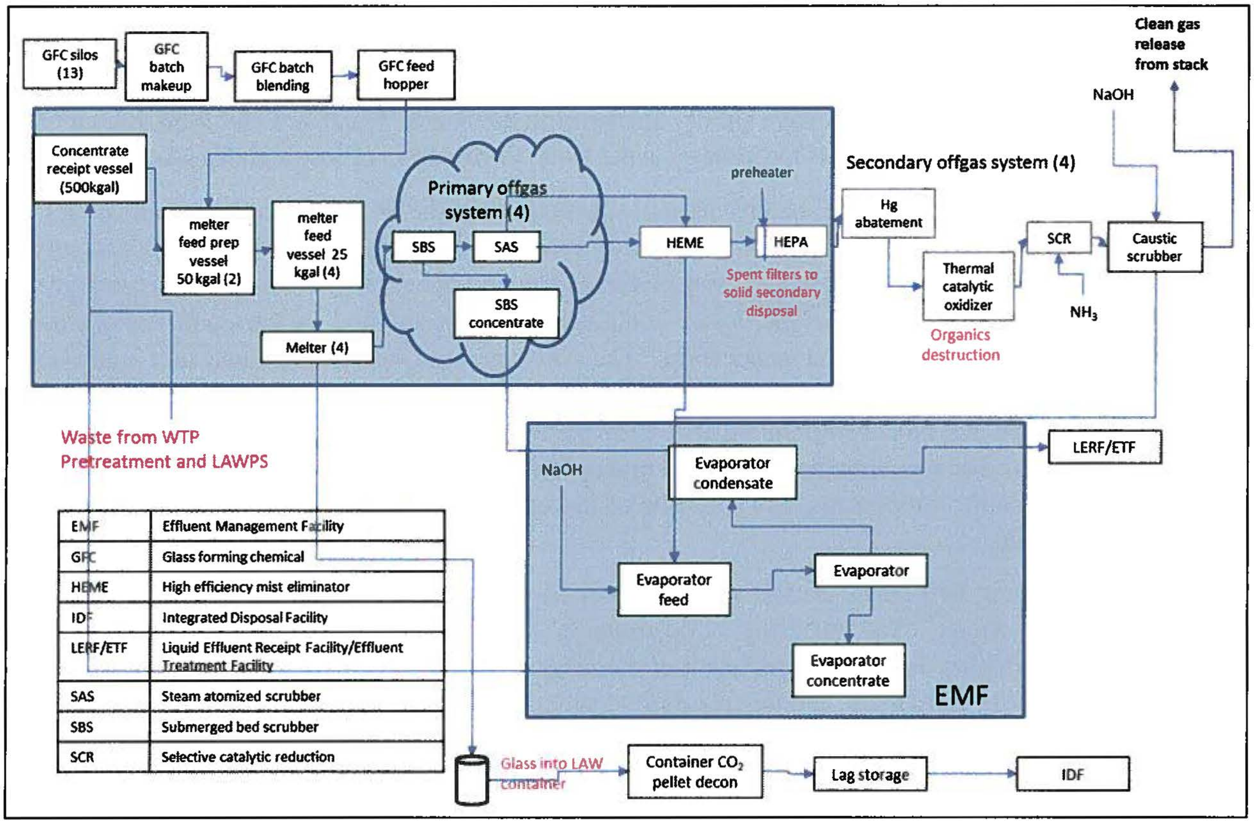
For Bulk Vitrification, SLAW will receive treated supernate from the WTP PT and LAWPS.[1] Pre-blended GFCs and sugar or cellulose (reductant) are added to the waste. The waste and additives are blended and dried into melter feed. The dried feed is added to the melt container as melting occurs. Heating is provided though graphite electrodes that transfer the alternating electrical current through the dried waste.[5] Offgas from the melt are captured by a hood sealed to container and will be treated similar to the offgas train in the first technology described above.

5.2.1 Description of Flowsheet(s)

Three flowsheets will be described here. The "baseline" 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. The second flowsheet incorporates "next generation melters" with an increase throughput and changing the glass container materials of construction from stainless steel to carbon steel. The final flowsheet evaluates the use of the In-Container Vitrification (ICV) glass containers for disposal at either the Integrated Disposal Facility (IDF) or an offsite LAW disposal facility.

5.2.1.1 Baseline

The baseline flowsheet consists of 1) melter feed systems that include receipt and handing of treated waste from PT and LAWPS, as well as GFC handling and blending; 2) four melters; 3) four offgas trains (primary and secondary); 4) an EMF (the EMF currently under design is sized to support LAWPS only, not Supplemental Treatment); 5) and a glass container handing, decontamination, and temporary lag storage facility.



5.2.1.1.1 Melter Feed System

Treated waste from PT and LAWPS will be received into a 500 kgal concentrate receipt vessel (CRV) and blended. The vessel with have ongoing in/out transfers. Blended waste will be transferred into two 50 kgal melter feed preparation vessels (MFPV). Each MFPV is sampled and analyzed to input into the glass property models to determine the GFC additions required. Based on the glass property models output, GFCs will be weighed from each of the 13 GFC silos, batched, blended, transferred to the GFC hopper. The blended GFCs will be added to the MPFV. After the GFCs and treated waste are blended, the slurry is transferred to four 25 kgal melter feed vessels (MFV). One MFV will feed each melter.

5.2.1.1.2 Melters

Melter feed from the MFVs will be fed to each of the four melters. The melters are joule-heated, ceramic-lined vessels heated to ~1150 °C to vitrify the waste. Each melter can produce 15 metric tons of glass per day.[6] The resulting glass is poured using an air lift in a riser where it will gravity drain into a stainless steel LAW container. 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. For reference, the SRS Defense Waste Processing Facility (DWPF) returns 5 gallons of liquid to the tank farm for each gallon of sludge vitrified.[7]

5.2.1.1.3 Offgas Trains

The offgas generated from each of the melters will be cooled via a film cooler and enter the primary offgas train. The cooled offgas will be condensed in a submerged bed scrubber (SBS). As the offgas is condensed, the concentrate from the SBS will be transferred to the EMF evaporator feed tank. The offgas passes through a steam atomized scrubber (SAS) to remove additional particulates. The offgas will then enter the secondary offgas train. Condensed liquids from the SAS will be recycled to support the high efficiency mist eliminator (HEME) that will remove soluble components and protect the high efficiency particulate air (HEPA) filter from moisture. The HEPA filter will remove any remaining particulates from the offgas. Spent HEPA filters will be transferred to the Central Waste Complex for encapsulation as Secondary Solid Waste prior to disposal at the IDF.[8] The resulting offgas will exit the radioactive containment area and will be treated to remove mercury. Any remaining organics will be destroyed using thermal catalytic oxidation. The NO_x will be reduced to nitrogen with ammonia using selective catalytic reduction, and finally, any remaining acid gases will be neutralized in a caustic scrubber. The caustic scrubber solution will be transferred to the LERF/ETF. Offgas exiting the caustic scrubber will be released to the stack.

5.2.1.1.4 Effluent Management Facility

The WTP 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. The effluent will be concentrated in the EMF evaporator. Concentrate will be recycled back into the CRV for immobilization and condensate will be transferred to the LERF/ETF for additional treatment.

5.2.1.1.5 Glass Containers

The vitrified waste is poured into stainless steel containers that hold ~6 metric tons (~2,000 gal) of vitrified waste.[6] The containers are cooled, inspected for fill height (if fill height is not ≥ 90%, inert fill is added), and sealed. The sealed container is decontaminated with CO_2 pellets and stored until transferred to the IDF.

5.2.1.2 First Alternative Flowsheet – 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.

5.2.1.3 Second Alternative Flowsheet – Next Generation Melters using Bulk Vitrification Containers

The second alternative flowsheet will maintain the waste feed preparation systems and methodology of the baseline flowsheet. This flowsheet uses the NGMs described in the first alternative flowsheet, however the vitrified waste will be poured into containers specified for the Bulk Vitrification process.[9] The containers will be transferred to either the IDF or an offsite LAW disposal facility.

5.2.1.4 Bulk Vitrification Flowsheet

The Bulk Vitrification technology review is underway and will be evaluated more closely in future revisions.

5.2.2 Assumptions

5.2.3 Risks

5.2.4 Benefits and Cost Estimate (Project and Lifecycle)

5.2.5 Schedule

5.2.6 Regulatory Compliance (Process, Transport, Disposal/Waste form)

5.2.7 Obstacles

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[1] "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.

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

[3] "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.

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

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

[6] "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.

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

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

[9] "Waste-Form Qualification Compliance Strategy for Bulk Vitrification," PNNL-15048, Pacific Northwest National Laboratory, Richland, Washington, 2005.

Grout Treatment for Hanford Supplemental Low Activity Waste

Table of Contents

BACKGROUND

Technology Overview

The reagents used in cementation processes are inorganic materials which 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. Grouting has also been used to encapsulate radioactive particulate waste and debris [IAEA, 2018 in press].

Two types of cement systems, hydraulic cements and acid-base cements, are used for radioactive waste treatment / conditioning. The most common hydraulic cements used are based on Portland cement, which is a mixture of anhydrous calcium silicates, calcium aluminate, and calcium sulfate compounds which react with water to form hydrated cementitious phases. Portland cement is often blended with other hydraulic and / or pozzolanic ingredients to meet specific waste stream production and performance requirement. Calcium aluminate cements, calcium sulfoaluminate cements, lime-pozzolan cements, calcium sulfate cements, and alkali activated slags and slag cements have also been successfully used for radioactive waste treatment. The most common acid-base cements used for radioactive waste conditioning are made by combining an acid (e.g., H_3PO_4 or KH_2PO_4, liquid or powder, respectively) with a powder base, e.g, MgO or CaO.

Grout technology can be tailored for a range of waste chemistries, available cement ingredients, and process, and final waste form requirements. Grout waste forms can also chemically bind certain radionuclides and hazardous contaminants by precipitation, co-precipitation, of low solubility phases, ion substitution in 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.

Analogue Grout Processes for Hanford Supplemental Low Activity Waste

Grout technology has been used in the DOE complex to treat (1) LAW (decontaminated salt waste from reprocessing facilities) at the Savannah River Site (SRS) and at the West Valley Demonstration Project (WVDP) and (2) other tank waste, e.g., low-level supernate from the Oak Ridge National Laboratory (ORNL) Research and Development Facilities. The grouted waste at WVDP was containerized in 19,962 71 gallon square drums each containing about 40 gallons of decontaminated tank supernate [DOE/EIS-0337-SA-01, 2006]. Shipment to NTS was completed in 2006. The grouted ORNL monoliths were cast into large, 1.8 meters tall and 1.8 meters in diameter, high integrity containers and shipped to NTS for disposal beginning in 2000 [Thomas and Guay, 2001].

At the SRS, grouting technology was designated as Best Developed Available Technology (BDAT) for LAW, and the resulting waste form is referred to as saltstone. Over 17 million gallons liquid waste have been treated and disposed in the SRS Saltstone Facility since 1991. The feed solution to saltstone is decontaminated with respect to Cs, Sr and actinides prior to being transferred to Tank 50, the 1M gallon tank that supplies feed to the process. Tank 50 is located in the H-Area tank farm about 1.6 miles from the saltstone processing facility. Salt solution is transferred from Tank 50 through a double jacketed line to the grout plant where it is mixed with a blend of Portland cement, blast furnace slag, and Class F fly ash (10:45:45 by weight). This reagent blend is mixed with the liquid waste in a water to dry blend ratio of 0.60. The addition of blast furnace slag provides a chemically reducing environment in the waste form which helps to maintain a low activity of oxygen, thereby providing chemical stabilization to selected redox sensitive contaminants, such as pertechnetate and chromate (TcO_4^- and CrO_4^{2-}).

Several similar dry-blend mixes have been investigated for various Hanford waste streams, with the resulting product termed Cast Stone. One recipe that has favorable properties for Hanford LAW streams, has the following dry blend proportions: 8 wt.% Portland cement, 47 wt.% blast furnace slag, 45 wt% Class F fly ash [Lockrem, 2005. Other proportions of dry blends have also been investigated [Lockrem, 2005; and Sundaram, et. al, 2011; Westsik, et. al, 2013 and Serne et al., 2016].

SLAW GROUT FLOWSHEETS

A base case SLAW flowsheet and two alternative flowsheets were developed and are described here. The Base Case is similar to the SRS saltstone facility but includes containerization. Grouted waste containerization processes have been demonstrated at several DOE sites including WVDP, ORNL, and SRNL. Alternative 1 is the Base Case plus pretreatment to remove contaminants that could present regulatory or performance issues for disposal. Both the base case and Alternative 1 have processing facilities located at or near WTP and both have two disposal options that will be considered, on-site at IDF and off-site at WCS. Alternative 2 is the same as the Base Case but the grout processing facility is located near the IDF and IDF is the only disposal case evaluated.

The feed vector for all the SLAW grout options is was described in elsewhere in this document.

Base-Case Grout Flowsheet

The Base Case SLAW grout flowsheet (simplified) is shown in Figure 1. The facility is expected to consist of the following unit operations:

- Dry-blend material delivery station and silos for the dry-blend materials (outside the radioactive control area)
  - Four silos are currently planned. The actual number of silos will depend on the final mix and facility design / operation.
- Metering and pneumatic transfer system from silos to blending tank
- Container receipt station (outside the radioactive control area)
- Transfer system for moving empty containers into process room and filled containers out of process room and into a decontamination area and then into the lag storage area.
- 500,000 gallon waste concentrate receipt tank located at grout plant which provides for about 40 days of surge storage capacity based on the feed vector information and a process feed rate of about 8 gpm (maximum feed volume).
- Reagent blending silo
- Blended reagent feed hopper and metering / delivery system into mixer
- SLAW transfer and metering system into mixer
- Mixer / processor
- Transfer system for filling container with grout
- Container closure station
- Container decontamination station – dry decontamination
- Curing and lag storage area
- Filled container loading facility for truck or rail transportation to disposal facility
- Secondary waste management
  - Secondary waste is expected to consist of dry decon waste, ventilation waste for ambient temperature radioactive processing, and job control waste.
- The grout facility control room is expected to be located in the facility.
- Laboratory support location for the grout facility is TBD

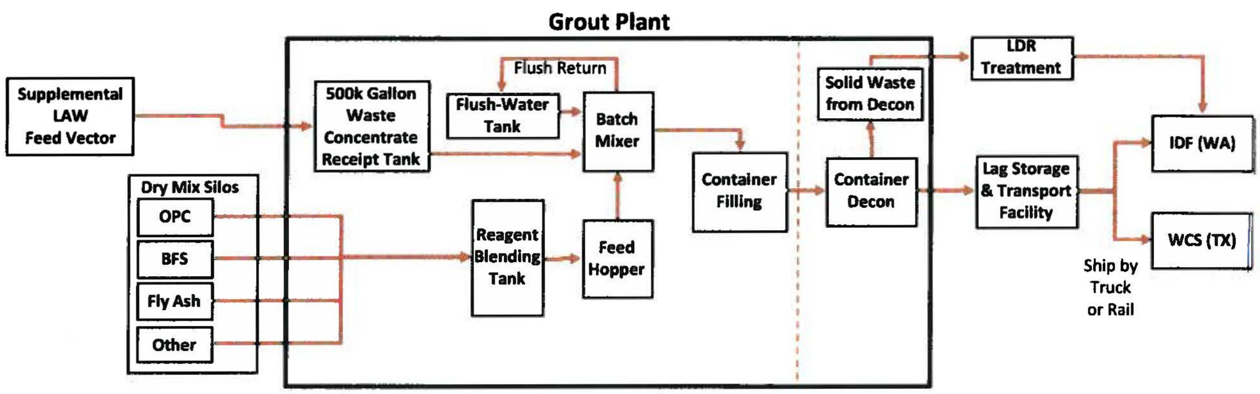

Figure 1. Base-case grout process. Grout facility located near the Waste Treatment Plant (WTP), no additional pre-treatment beyond WTP-PT/LAWPS, and disposal at either IDF or WCS.

Alternative 1 Grout Flowsheet

Alternative 1 (Figure 2) is the same as the base case grout flowsheet except it includes additional pretreatment of the supplemental LAW prior to entering the grout facility. This flowsheet is applicable only if SLAW pretreatment is needed or beneficial for the grouted waste form. The drivers for considering pretreatment are: regulatory compliance, disposal site WAC and / or transportation cost optimization. The need for pretreatment does not depend on processing reliability.

Currently, pretreatment is being considered / evaluated for Tc-99 and I-129 with respect to meeting the IDF PA. Grouted waste containing Tc-99 and I-129 meets the WCS WAC, regardless of the chemical makeup of these radionuclides, without additional chemical stabilization. However, this may not be the case for the IDF WAC. Pretreatment for organics in the waste is being evaluated with respect to waste classification and meeting LDR treatment standards. Ammonia abatement may be needed to meet air permit requirements during processing and possibly during curing [SRNL-L3100-2016-00165]. Pretreatment to remove most of the Sr-90 is being considered to lower the transportation cost (Type A versus Type B shipping container) if an off-site disposal site is selected.

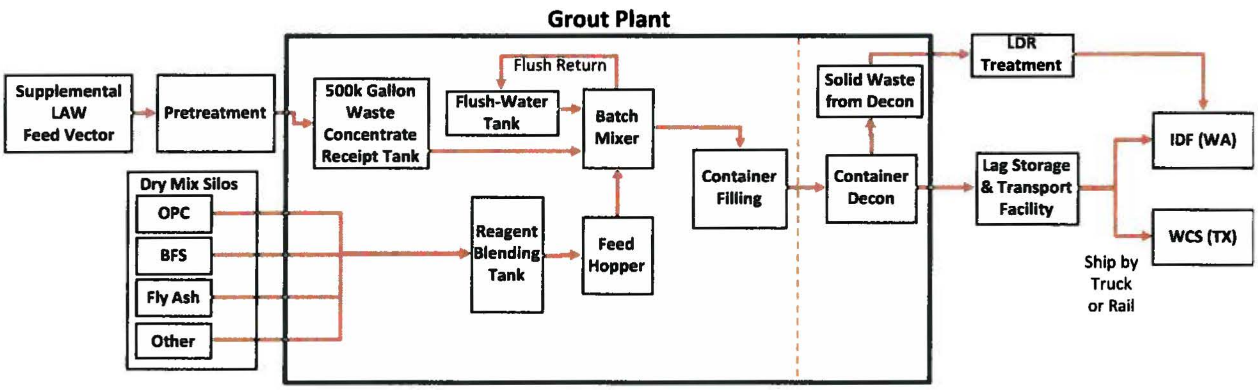

Figure 2. Process-flow diagram for Alternative 1. Similar to base case except with additional pretreatment of liquid feed vector prior to entering grout plant.

Alternative 2 Grout Flowsheet

Alternative 2 (Figure 3) is the same as the base case grout flowsheet, except that the grout plant is located near the IDF and, instead of discharging into a transportable container, the grout is pumped to a large disposal unit located in the IDF. This alternative requires construction of a jacketed pipeline from WTP to IDF to deliver the supplemental LAW feed to the grout facility. After mixing, the slurry would be pumped into large disposal units (probably constructed of reinforced concrete) where it would solidify in place. This alternative eliminates the need for handling and transporting containers. The location of the grout plant would be such as to minimize the distance the grout must be pumped. This alternative is similar to the SRS saltstone process and disposal units which have a range of capacities from about 2 to 32 M gallon capacity.

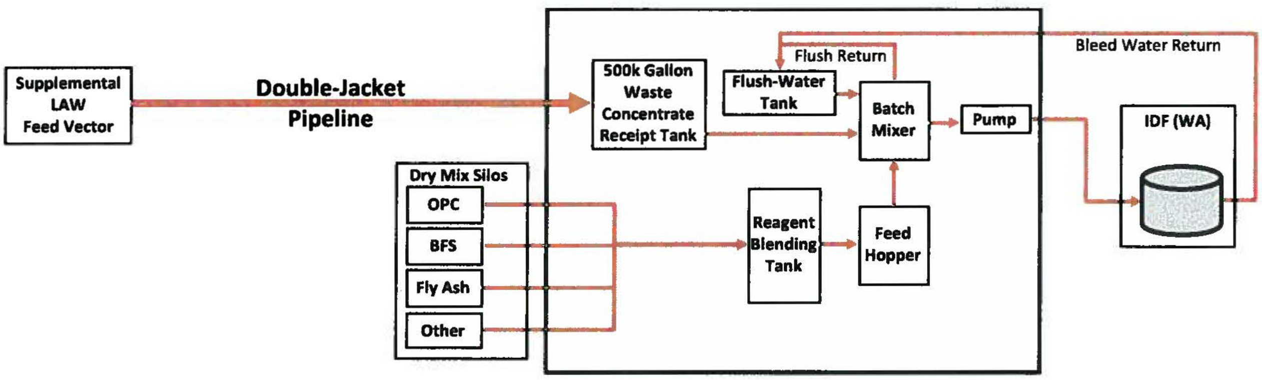

Figure. 3. Draft process-flow diagram for Alternative 2. Similar to base case except with the grout facility located near the IDF and containerization in place at IDF.

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FLUIDIZED BED STEAM REFORMING FOR HANFORD SUPPLEMENTAL LAW TREATMENT

CONTENTS

1. INTRODUCTION

Fluidized bed steam reforming (FBSR) has been researched, developed, and used commercially for over two decades for processing low level radioactive wastes. The commercial Studsvik Processing Facility 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). 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.

Selected FBSR research and development programs for treating various liquid radioactive wastes performed between 2001 and 2011 are summarized in Table 1-1. 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 waste form. Steam reforming has also been developed and demonstrated to produce a granular carbonate-based product; that, while solidified to eliminate the liquid component of INL's SBW, or Savannah River Site's Tank 48 waste, is not intended to be leach-resistant. Studsvik, Inc. has also continued to develop and demonstrate steam reforming for various world-wide customers. Various references for this table and for other tests include: Marshall 2003, Olson 2004a, Olson 2004b, Soelberg 2004a, and Soelberg 2004b.

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. 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 (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 was 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.

The concept of steam reforming for Hanford Supplemental LAW treatment is based on the goal to produce a durable mineral, not leachable carbonate, product. Table 1-2 summarizes considerable research and development for the FBSR mineralized waste form performed in conjunction with the FBSR testing (SRNL-ORNL-PNNL-WRPS down-select [Jantzen 2015]).

1.1 What is Mineralizing Fluidized Bed Steam Reforming

Steam reforming is broadly defined as a process in which superheated steam is used to crack and oxidize 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 salts, mineral acids, alkali hydroxides, or residual organic solvents are chief candidates for steam reforming.

Figure 1-1 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 preheated to nominally 500-600°C prior to entering the DMR.

Coal and oxygen are fed into the DMR where they react (also with some of the steam) to (a) heat DMR to the target mineralizing operating temperature of around 750°C, and (b) produce H_2 and other reduced gas species such as CO and CH_4 that can react with the nitrates in the waste feed, converting the nitrates 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, with small residual amounts of reducing gases in the DMR outlet gas. 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
- 3-5 vol% H_2
- 1-2 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 1-1. Summary of selected FBSR research and demonstration programs since 2001, through 2011 (Jantzen 2015).

<table>
<tr><th>Facility</th><th>Scale</th><th>Radioactive or Non-Radioactive?</th><th>FBSR Column Diameter</th><th>Externally or Autothermaly Heated?</th><th>Dual or Single Reformer Flowsheet?</th><th>Reductant of Choice</th><th>Catalyst?</th><th>Waste</th></tr>
<tr><td>TTT 2001-2002</td><td>Pilot</td><td rowspan="3">Non-Radioactive</td><td>6"</td><td>external and autothermal with coal</td><td>Single</td><td>BB charcoal</td><td>Yes</td><td>AN-107</td></tr>
<tr><td>SAIC-STAR 2003-2004</td><td>Pilot</td><td>6"</td><td>external and autothermal with coal</td><td>Single</td><td>BB charcoal</td><td>No</td><td>INTEC SBW Rassat LAW</td></tr>
<tr><td>TTT ESTD 2006</td><td>Engineering</td><td>15"</td><td>autothermal with coal</td><td>Dual</td><td>Bestac coal</td><td>Yes</td><td>INTEC SBW</td></tr>
<tr><td>TTT ESTD 2008</td><td>Engineering</td><td>Non-Radioactive</td><td>15"</td><td>autothermal with coal</td><td>Dual</td><td>Bestac coal</td><td>Yes</td><td>WTP-SW (Module A)</td></tr>
<tr><td>SRNL BSR 2009</td><td>Bench-scale</td><td>Radioactive and Non-Radioactive</td><td>2.75"</td><td>external and autothermal with coal</td><td>Dual</td><td>Bestac coal</td><td>No</td><td>WTP-SW (Module A)</td></tr>
<tr><td colspan="9">START OF THE DOE-EM WFQ PROGRAM</td></tr>
<tr><td>TTT ESTD 2008</td><td>Engineering</td><td>Non-Radioactive</td><td>15"</td><td>autothermal with coal</td><td>Dual</td><td>Bestac coal</td><td>Yes</td><td>Rassat LAW (Module B)</td></tr>
<tr><td>SRNL BSR 2010-2011</td><td>Bench-scale</td><td>Radioactive and Non-Radioactive</td><td rowspan="2">2.75"</td><td rowspan="2">external and autothermal with coal</td><td rowspan="2">Dual</td><td rowspan="2">Bestac coal</td><td>Some tests</td><td>Rassat LAW (Module B) SX-105 (Module C) AN-103 (Module D)</td></tr>
<tr><td>SRNL BSR 2011</td><td>Bench-scale</td><td>Non-Radioactive</td><td>Yes</td><td>AZ-101/ AZ-102 (Module E)</td></tr>
</table>

WTP-SW = WTP Secondary Waste

Table 1-2. Summary of FBSR mineralized waste form studies (SRNL-ORNL-PNNL-WRPS downselect 2015).

Pilot Scale Facility	Date	FBSR Diameter	Acidic And Basic Wastes	Granular PCT Testing	TCLP of Granular Form	Granular SPFT Testing	Preliminary Risk Assessment	Product Tested	Coal	Particle Size Distribution (PSD)	MonoLith	Monolith PCT Testing	Monolith SPFT Testing	MonolithANSI/ANS 16.1/ ASTM C1308 Testing	TCLP of Monolith
Non-Radioactive Testing															
HRI/ TTT	12/01 Ref 60	6"	LAW Env. C AN-107	Ref. 115	Ref 60,115	Ref 61,105 and PUF testing (106)	Ref. 107	Bed	Removed By Hand	Gaussian	No	N/A			
		6"		Ref 111,112,113		None	"Tie-back" Strategy 3	Fines	Removed by 525°C Roasting						
SAIC/ STAR	7/03 Ref 103, 104	6"	SBW			None	None	Bed			Yes (Samples were combined; 20% LAW, 32 % SBW and 45% Startup Bed)	Ref 116,117	N/A		
SAIC/ STAR	8/04 Ref. 108	6"	LAW Rassat			Ref 6,113 , 118,119 and PUF 6,120	Data from Ref 113,118,119 "Tie-back" Strategy 3	Bed and Fines Separate							
SAIC/ STAR	7/04 and 11/04 Ref. 110	6"	SBW			Ref 113,118	None								
HRI/ TTT	12/06	15"	SBW	Ref 121		None	None				No	N/A			
HRI/ TTT	2008 Ref. 122		LAW Rassat	Ref 3,98 , 123,124, 125	Ref 123, 124, 125	126	"Tie-back" Strategy 3	Bed and Fines Together	Not removed	Bi-Modal	Yes	Ref 123	PNNL	Ref 3	
			WTP-SW			None	None						None	Ref 127, 128	Ref 123,124 125
Radioactive Testing															
SRNL/ BSR	2010-2013	2.75"	LAW Rassat	Ref. 3, 129		126,130 and PUF 131 ,132	"Tie-back" Strategy 3	Bed and Fines Together	Not removed	Gaussian	Yes	Ref 3	Ref 130	Ref 3	
			WTP-SW	Ref 127,129		None	None					Ref 127	None	Ref 127	Ref 127

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 emersion tests all similar with different leachate replenishment intervals; Pressure Unsaturated Flow Test (PUF); -LAW Env. – low activity waste envelope A, B, and C; PSD - particle size distribution; FY11 – Joint program between SRNL, PNNL, ORNL; SRNL Test Results are complete and documented [3,4] PNNL Test Results are complete and documented; N/A – not applicable.

The waste feed is premixed with clay (aluminum-silicon oxides), to react with the Na and other nonvolatile and semivolatile elements in the waste feed. The resultant mixture is a liquid-solid slurry because the clay does not appreciably dissolve. 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 LAW (Na, lesser stable 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).

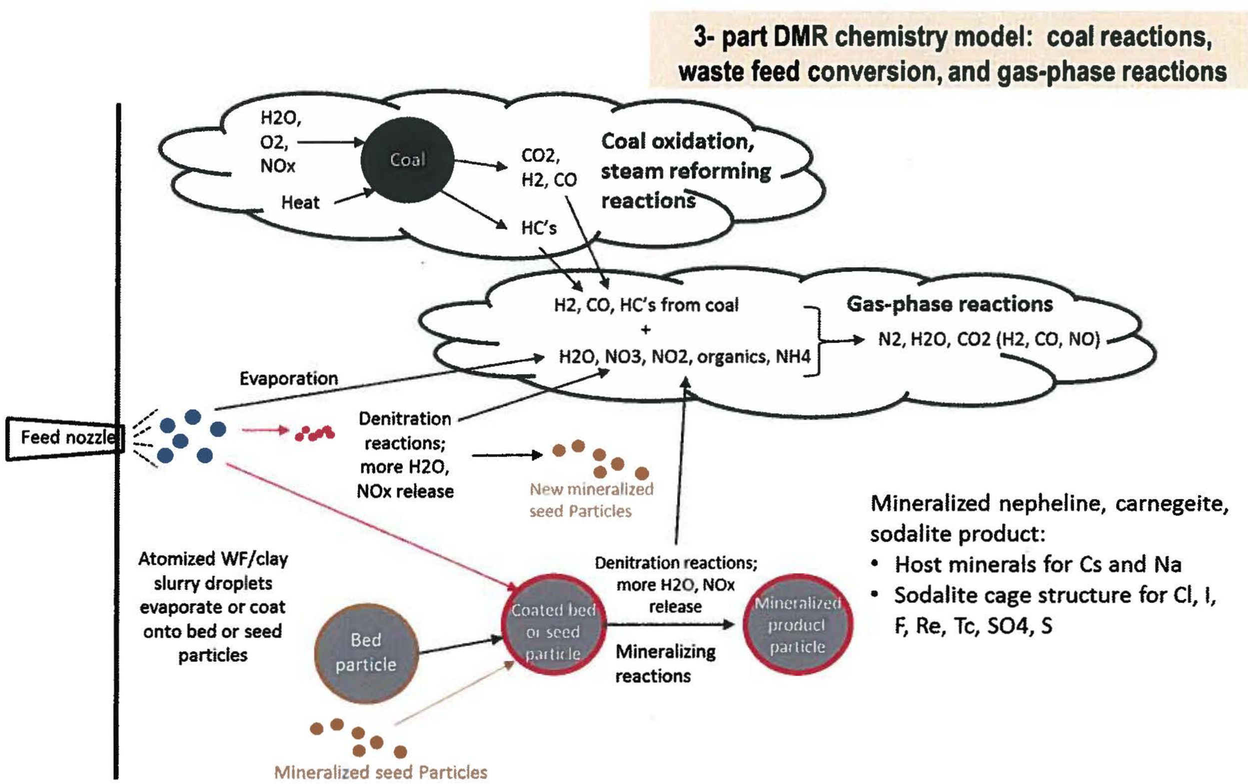


Figure 1-1. Three-part DMR chemistry model: coal reactions, waste feed conversion, and gas-phase reactions.

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 1-2 illustrates a fluidized DMR vessel. Primary features include:

- Haynes 556 alloy or equivalent for strength and corrosion tolerance at temperatures ~750°C (no refractory).
- Steam, O_2, and N_2 fluidizing gas flows up from bottom.
- Heated by coal oxidation.
- O_2-deficient pyrolysis destroys both organics and NO_x.
- 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.

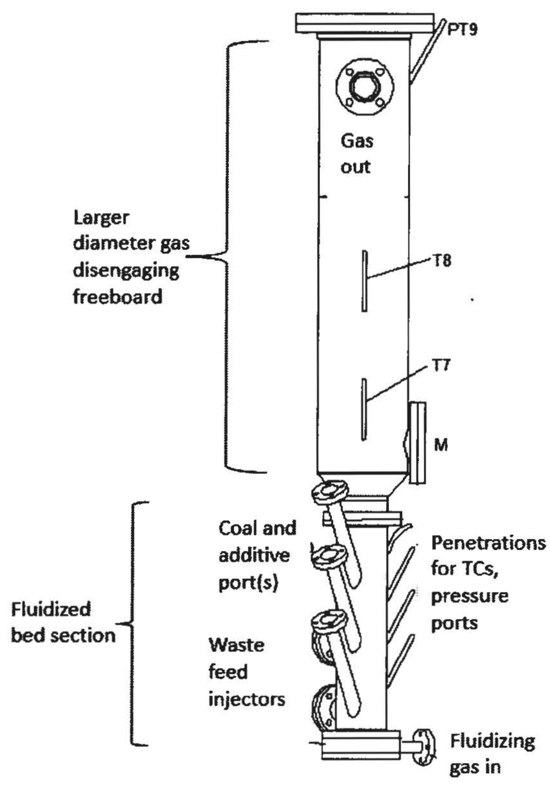


Figure 1-2. Illustration of a fluidized DMR vessel (from Olson 2004a).

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

Feldspathoid mineral structures that represent the kinds of desired mineral forms in the durable, leach-resistant waste form are shown in Table 1-3. These nepheline, carnegieite, sodalite, and nosean structures can incorporate the nonvolatile and semivolatile elements in the waste feed either into the mineral structure or inside "cages" of suitable sizes that contain some of key halogens and radionuclides (SRNL-ORNL-PNNL-WRPS downselect 2015).

1.2 How Fluidize 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 1-4 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 1-3. Substitutional cations and oxy-anions in feldspathoid mineral structures (from Jantzen 2015).

Nepheline – Kalsilite Structures*	Carnegieite Structures	Sodalite Structures**	Nosean Structures
$Na_xAl_ySi_zO_4$ [63] *where x=1-1.33, y and z = 0.55-1.1(H)*	$NaAlSiO_4$ high carnegieite (C) [64; PDF #11-221]	$[Na_6Al_6Si_6O_{24}](NaCl)_2$ [63,65,66]	$[Na_6Al_6Si_6O_{24}](Na_2SO_4)$ [63,67,68]
$NaAlSiO_4$ [PDF #052-1342;69] (O)[t]	$NaAlSiO_4$ low carnegieite [64; PDF #11-220 no symmetry given]	$[Na_6Al_6Si_6O_{24}](NaFl)_2$ [63]	$[Na_6Al_6Si_6O_{24}](Na_2MoO_4)$ [63,70]
$KAlSiO_4$[63]	$Na_{1.45}Al_{1.45}Si_{0.55}O_4$ [71,72]	$[Na_6Al_6Si_6O_{24}](NaI)_2$ [11,68]	$[Na_6Al_6Si_6O_{24}]((Ca,Na)SO_4)_{1\text{-}2}$ [73]
$K_{0.00}Na_{1.00}AlSiO_4$ to $K_{0.25}Na_{0.75}AlSiO_4$ solid solution [63]	$Na_{1.95}Al_{1.95}Si_{0.05}O_4$ [71,72]	$[Na_6Al_6Si_6O_{24}](NaBr)_2$ [68]	$[(Ca,Na)_6Al_6Si_6O_{24}]((Ca,Na)S,SO_4,Cl)_x$ [PDF[f] #17-749]
$(Na_2O)_{0.33}NaAlSiO_4$ [74] (C)	$Na_{1.75}Al_{175}Si_{0.25}O_4$ [71,72]	$[Na_6Al_6Si_6O_{24}](NaReO_4)_2$ [75]	
$CsAlSiO_4$ [63]	$Na_{1.65}Al_{165}Si_{0.35}O_4$ [71,72]	$[Na_6Al_6Si_6O_{24}](NaMnO_4)_2$ [76,77]	
$RbAlSiO_4$ [63]	$Na_{1.55}Al_{155}Si_{045}O_4$ [71,72]	$[NaAlSiO_4]_6(NaBO_4)_2$ [78,79]	
$(Ca_{0.5},Sr_{0.5})AlSiO_4$ [63]	$Na_{1.15}Al_{115}Si_{085}O_4$ [71,72]	$(Fe,Zn,Mn)_4[Be_3Si_3O_{12}]S$ [68]	
$(Sr,Ba)Al_2O_4$ [63]	$Na_3MgAlSi_2O_8$ [71,72]	$Sr_8[Al_{12}O_{24}](CrO_4)_2$ [80]	
$KFeSiO_4$ [63]		$Na_8[AlSiO_4]_6(SCN)_2$ [81]	
$(Na,Ca_{0.5})YSiO_4$ [76]		$Na_6Al_6Si_6O_{24}$ (Zeolite A) [82,83]	
$(Na,K)LaSiO_4$[76]		$Na_8[ABO_4]_6{\cdot}X_2$, where A=Al and Ga, B=Si and Ge, and X includes Cl^-, Br^-, I^-, $(ClO_3)^-$, $(BrO_3)^-$, $(HCOO)^-$, $(MnO_4)^-$, $(SCN)^-$ and $(SeCN)^-$ [84,85]	
$(Na,K,Ca_{0.5})NdSiO_4$[76]		$Na_{7.50}Fe^{2+}_{0.05}[Si_{6.07}Al_{5.93}]O_{24}Cl_{1.99}(SO_4)_{0.01}$ (hackmanite0 [86]	

* Iron, Ti^{3+}, Mn, Mg, Ba, Li, Rb, Sr, Zr, Ga, Cu, V, and Yb all substitute in trace amounts in nepheline.[63]

** 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 [76]

f Powder Diffraction File

t may be low-carnegieite per original reference

Note: (C) is for cubic crystal symmetry, (H) is for hexagonal crystal symmetry, (O) is for orthorhombic crystal symmetry (see text).

Table 1-4. Supplemental LAW treatment system feed vector monthly feedrate and composition data.

Parameter	Monthly average	Monthly turndown ratio (max/min)	Comments
SLAW feedrate, gpm	3.6	**51**	High turndown ratio needs feed tanks to achieve turndown ratio of ~2 per FBSR
WTP LAW vit feedrate, gpm	3.4	1.8	Steady flowrate presumably by design
Solids conc., wt%	3.3	126	Not relevant to FBSR which has much more added clay per L waste
Na conc., g/L	180	2	Vary clay or dilute feed
NO3 conc., g/L	110	6	Adequately destroyed by FBSR system
NO2 conc., g/L	30	11	
Hg conc., g/L			Need Hg control but necessary DF decreases after ~2035
Tc-99 conc., mg/L	3.2	36	Captured in product and wet scrubber (and recycled to DMR)
I-129 conc., mg/L	0.3	16	
S conc., mg/L	56	470	
Organics, NH3, NH4 conc.	Not relevant		Adequately destroyed by FBSR system

2. FBSR PROCESS FLOW OPTIONS AND DIAGRAMS

Two FBSR options are proposed, based on the desired waste form. Option 1 (Figure 2-1) provides a durable, mineralized granular waste form for storage and permanent disposal. Option 2 (Figure 2-2) provides additional treatment of that waste form to convert it to a monolith, eliminating potentially dispersible waste form fines (dust) and increasing the waste form compressive strength.

Two feed vector conditions combine to define two primary features of the FBSR treatment system. Figure 2-3 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.
- ~1,000,000 gal additional delay tank + two 250,000 gal waste feed/mix tank capacity needed for first ~3 years of SLAW treatment; throughput decreases afterwards.
- Two identical FBSR systems to maximize available capacity in first ~3 yrs.
- Shared waste staging, mixing, and feed system.

The figure show that the core DMR and PGF are actually only two of many other 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.

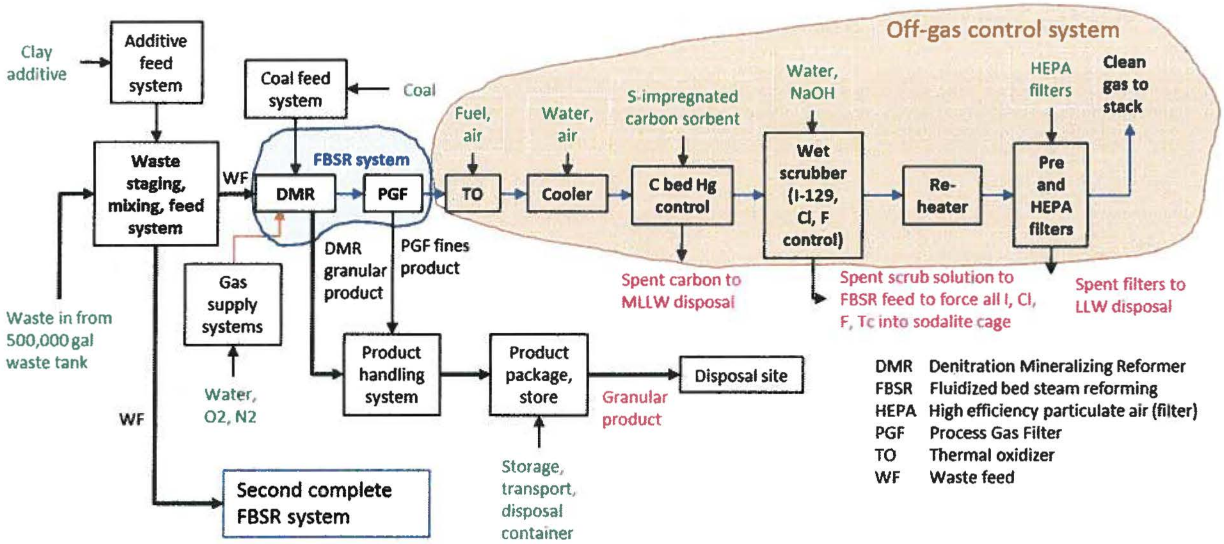


Figure 2-1. Mineralizing FBSR Option 1: Two DMR systems; dry granular solid product.

Option 2 has the same components that Option 1 has, but it includes a system that monoliths the granular DMR/PGF product. Converting the granular product to a solid monolith eliminates dust and provides more compression strength, in case those are desired for storage and permanent disposal. Option 2 has the same waste feed, FBSR and off-gas, and product handing systems as in Option 1. It includes two complete identical product monolith systems to maximize available capacity.

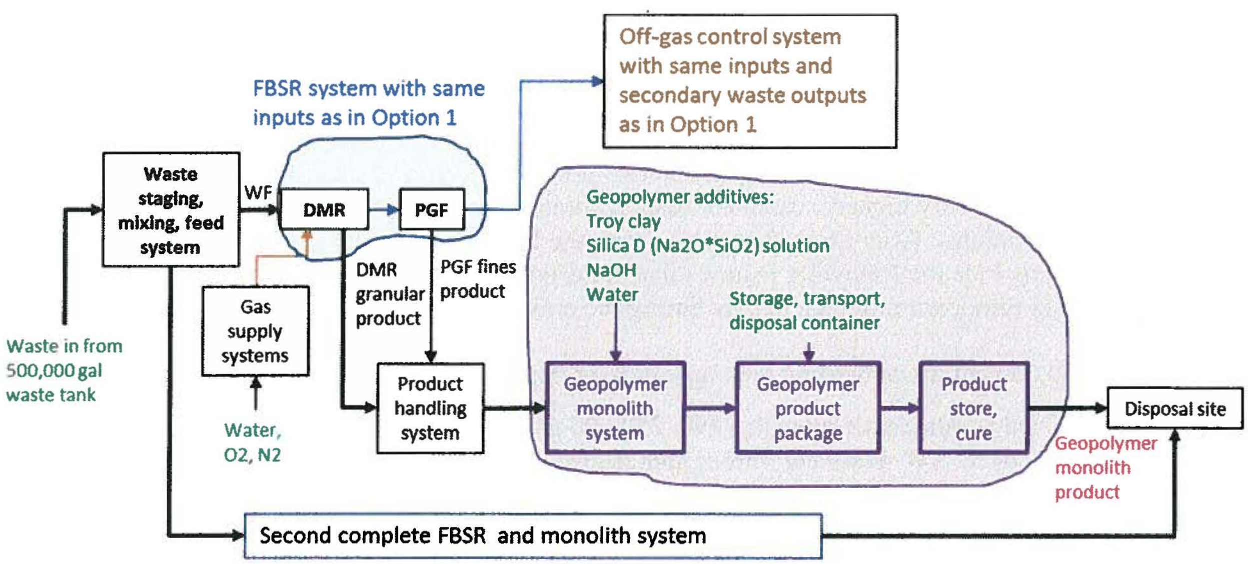


Figure 2-2. Mineralizing FBSR Option 2: Two DMR systems; solid monolith product.

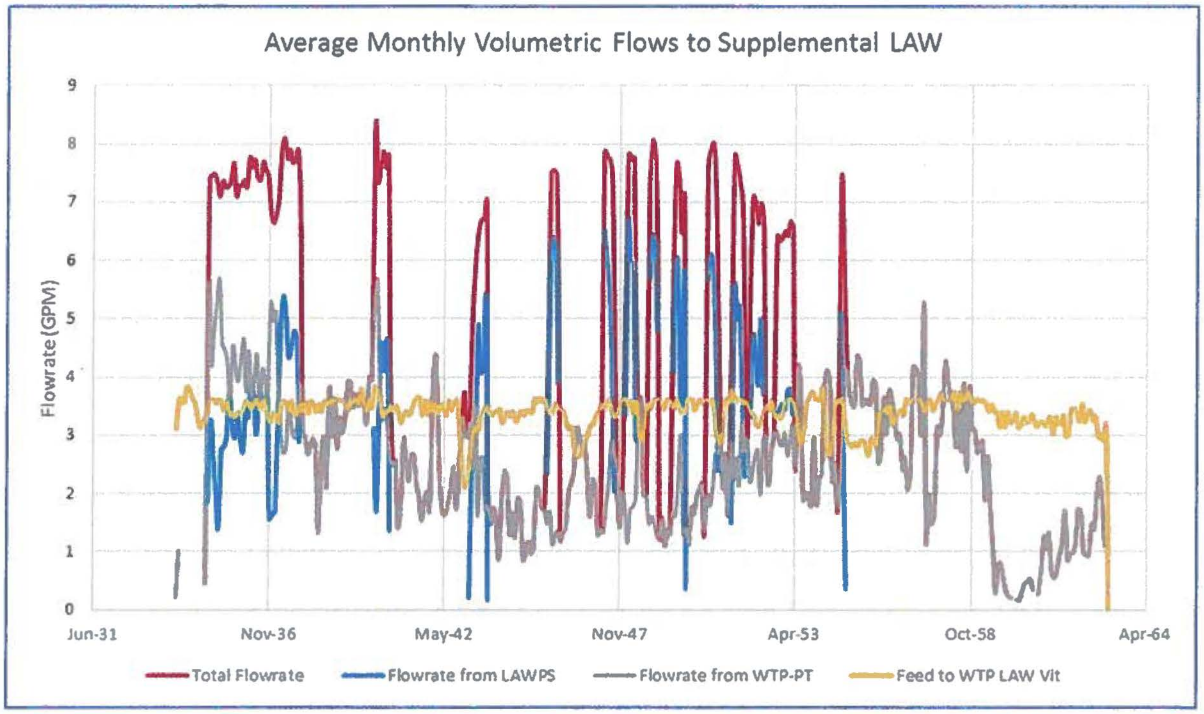


Figure 2-3. Variation in the monthly Hanford LAW stream flowrates from the feed vector.

3. INITIAL FBSR MASS BALANCE

A mass-energy balance using HSC Chemistry with Excel inputs and outputs has been initiated to develop and track the fate of all input streams to the FBSR process, and estimate the flowrates and compositions of the output process gas flowrate and mineral product streams. Results to date are shown in Figure 3-1. This is the same model that is currently used to track the performance and mass balance of the IWTU. References for inputs to this model for the Hanford Supplemental LAW treatment process include the SLAW feed vector, the Advanced Remediation Technology pilot-scale Hanford LAW and Hanford WTP vitrification recycle stream mineralizing steam reforming test report (TTT 2009) and the FBSR mineral waste form downselect report (SRNL-ORNL-PNNL-WRPS downselect 2015).

When complete, the mass-energy balance model will calculate the mass and energy inputs and outputs through the rest of the process.

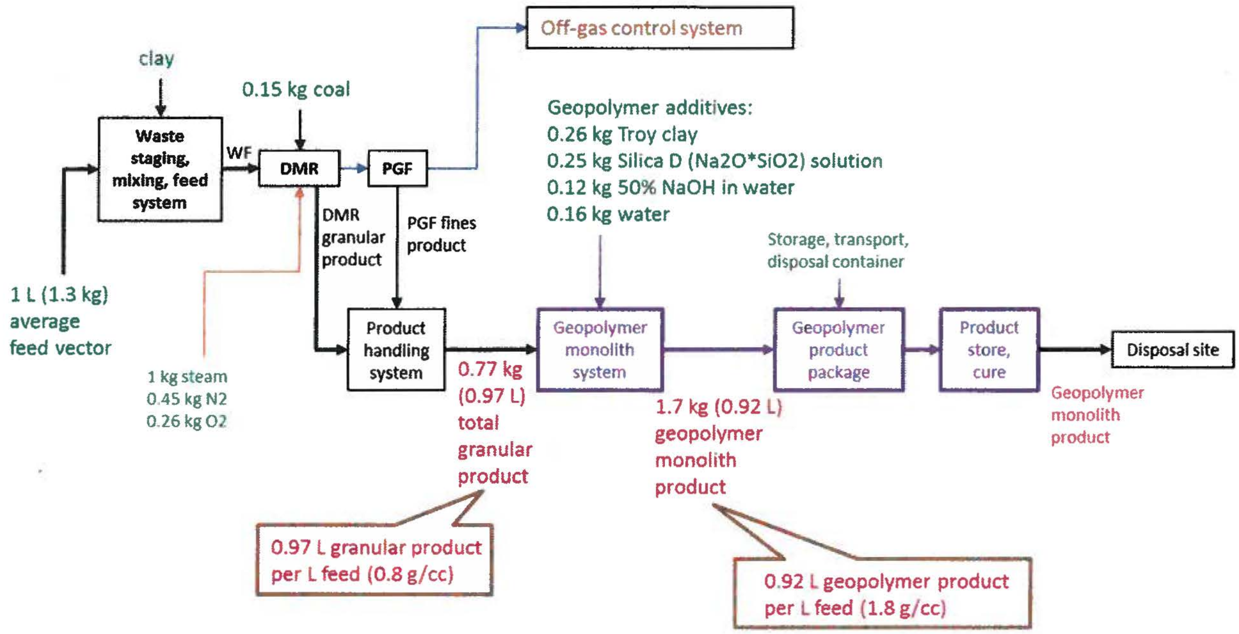


Figure 3-1. Initial mass balance results for FBSR treatment of Hanford SLAW.

4. MINERAL WASTE FORMS

The following high-level description of the target FBSR mineral waste form is extracted almost word-for-word from the FBSR mineral waste form downselect report (SRNL-ORNL-PNNL-WRPS downselect 2015). This reference, and references of this reference, contain extensive additional detail.

The FBSR technology forms a mineral waste form at moderate processing temperatures (700-750°C) in the presence of steam; retaining and atomically bonding the halides, sulfates, and Tc-99 in the mineral phases:

- Nepheline (nominally $NaAlSiO_4$ of hexagonal symmetry).
- 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).

All aluminate sodalites that host Sr and Cr are known (Table 4-1) and sodalites with a variety of Al:Si ratios are known. Sodalites also host B, Mn, Ge, Ga, Be, and S.

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.

Table 4-1. Comparison of target mineral phases formed FBSR, HLW ceramic waste forms, and glass-bonded sodalite waste forms.

Mineral Phases Formed in FBSR at ~700°C [60,61]	Mineral Phases Formed in HLW Ceramic Waste Forms [13,15-17,20-26]	Mineral Phases in Glass Bonded Sodalite Waste Forms [18,19,27,28]
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		

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).

4.1 Granular and Monolith Mineral Waste Forms

Figure 4-1 shows scanning electron micrographs of the granular mineralized waste form such as would be produced in Option 1. The individual particles from the fluidized bed range in size from under 10 microns to about 1 micron. Larger particles, especially of incompletely oxidized coal up to about 0.25 in. diameter (not shown in the figure), are also typically present and can be up to several weight percent of the total product mass.

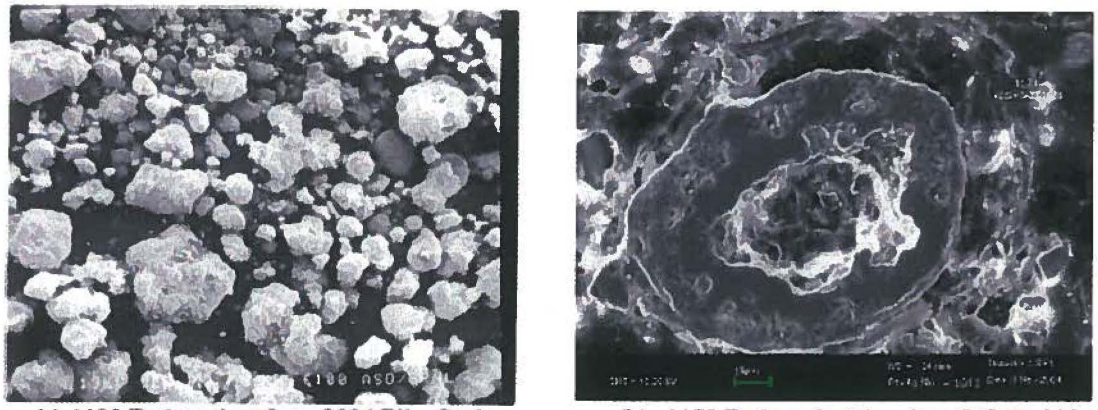
Figure 4-2 shows a photograph of a monolith of FBSR mineral product formed with additives into a geopolymer monolith, such as would be produced in Option 2.

4.2 Waste Form Mineralogy Control

Solid granular and monolith product WF composition and performance has been studied since 2001. 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 (Jantzen 2014 and SRNL-ORNL-PNNL-WRPS downselect 2015). The clay additive, depending on the input feed composition, would be a choice of fine-particle-sized clay commercially available and commonly used for many processes including the manufacture of porcelain fixtures (Figure 4-3).

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 Figure 4-4.

Table 4-2 and Figure 4-5 show how halogens, S, and Tc-99 can be captured in sodalite and nosean phases in durable "cages."



(a) 1123 Bed product from 2004 Pilot Scale Testing

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

Figure 4-1. 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 2015).

Figure 4-2. Troy clay geopolymer monolith of Hanford LAW 60% FBSR product (SRNL-ORNL-PNNL-WRPS downselect 2015).

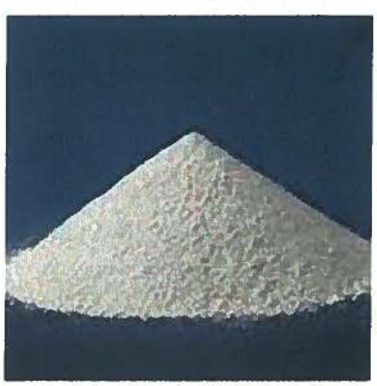


Figure 4-3. Typical commercially available clay.

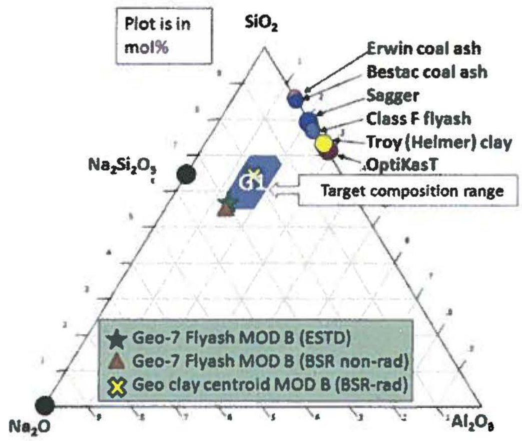


Figure 4-4. Target MINCALC Na_2O – Al_2O_3 – SiO_2 composition for a durable mineralized product.

Table 4-2. Oxidation states and atomic radii for common anions incorporated into the sodalite framework (SRNL-ORNL-PNNL-WRPS downselect 2015).

Element	Mineral Name	Oxidation State	Coordination Number	a(Å)	Space Group	Ionic Radii fom Ref. 6 (Å)	Ionic Radii from Ref. [96] (Å)
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							

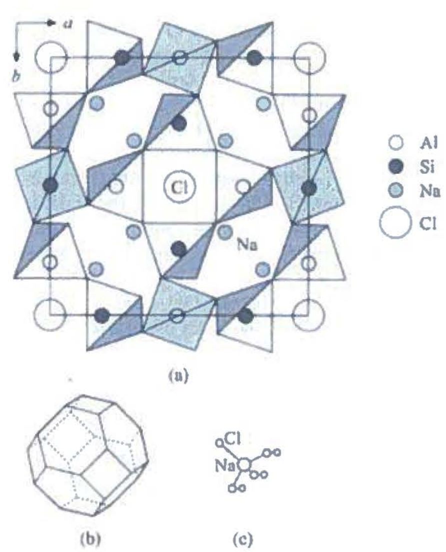


Figure 4-5. Structure of sodalite showing (a) 2-dimensional projection of the (b) 3-dimensional structure and (c) the 4-fold ionic coordination of the Na site to the Cl ion and 3 framework oxygen bonds (SRNL-ORNL-PNNL-WRPS downselect 2015).

4.3 Product Analyses and Durability Tests

This section contains information summarized from the FBSR mineral waste form downselect report (SRNL-ORNL-PNNL-WRPS downselect 2015). Durability tests have been performed on both granular and monolith products:

- 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 a 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).

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 nitrate 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.
- 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 [$(2.1 \pm 0.3) \times 10^{-2}$ g/(m^2d)] 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 SO4 sodalite/nosean endmembers and a mixed Re/Tc sodalite made at SRNL.

Tests performed on mineralized product monoliths are listed in Table 4-3. Results of these monolith tests are summarized below (SRNL-ORNL-PNNL-WRPS downselect 2015):

- 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 $\geq$ 9 after a few days and the LI for Na $\geq$ 6 in 2 hours.
- FBSR monoliths pass ANSI/ANS 16.1/ASTM C1308 durability testing with LI(Re) $\geq$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 4-3. Tests performed on monoliths.

Monolith	As Made Composition	Dry Basis Fbsr Loading (%)	Compress-Ion Tested	XRD Phases	PCT	Analyzed Chemical Composition	TCLP Testing	Bulk Density (G/Cc)	ANSI/ANS 16.1/ ASTM C1308 Leaching	SPFT/PUF Testing
Fly Ash GEO-7 ESTD LAW P-1B	Table 9-1	68	Yes	Yes	Short-Term and Long-Term	Yes	Yes	Yes	Yes	SPFT PUF
Fly Ash GEO-7 Mod B Sim	Table 9-2	68	Yes	Yes	Short-Term and Long-Term	Yes	Yes	Yes	Yes	SPFT
Clay ESTD LAW P-1B	Table 9-3	42	Yes	Yes	No	No[b]	No	Yes	Yes	No
	Table 9-4	65				No[b]	No	No	No	No
Clay Mod B Sim	Table 9-3	42	Yes	Yes	No	No[b]	No	Yes	Yes	No
Clay Mod B Rad	Table 9-5	42	Yes	Yes	Short-Term[a]	No[b]	Yes	No	No	No
	Table 9-4	65			Long-Term[a]	No[b]	Yes	No	No	No

a) Both the 42% WL and the 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 in this work.

b) Chemical compositions calculated from analyzed granular products and known Na, Al and Si oxide compositions of the binder additives.

5. AIR EMISSIONS COMPLIANCE AND RETENTION OF RADIONUCLIDES AND HAZARDOUS METALS

FBSR is expected to meet emission requirements similar to WTP LAW vitrification as shown in Table 5-1.

The combination of pyrolysis in the DMR and efficient oxidation in the thermal oxidizer is especially effective at destroying incoming organic compounds. Testing has demonstrated compliance to even the stringent HWC MACT standards for CO, total hydrocarbon, and dioxin emissions, and Principal Organic Hazardous Constituent (POHC) destruction. This pyrolysis/oxidation combination is also highly effective at destroying ammonia compounds. 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.

Mercury is not captured in FBSR product, but quantitatively evolves into the process gas stream, like it does in other thermal processes like vitrification. None is expected to be captured in the FBSR solid waste form. Instead, as is already designed and installed for the Hanford WTP LAW vitrification and the INL IWTU steam reforming processes, it would be captured in a fixed bed of S-impregnated activated carbon in the off-gas system. Figure 5-1 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.

Table 5-1. Expected FBSR off-gas control performance requirements.

Expected off-gas control performance requirements		
Parameter	Requirement or expected value	Basis
Stack gas NOx concentration	≤100-300 ppmv dry;	Pilot plant tests indicate this level is achievable; and it is assumed that this level of NOx emissions is regulatorily acceptable. (Need to confirm this based on WTP LAW vit NOx control requirements.)
WF organics destruction	≥99.99%	Assume bounding requirement is HWC MACT standards for principal organic hazardous constituents
Hg decontamination factor (DF)	≥450	Assume FBSR requirement is similar to WTP LAW vit requirements. 100% of the Hg evolves to the off-gas where it is controlled using sulfur-impregnated activated carbon. Test data shows that key radionuclides including Tc-99 and I-129, halogens Cl, F, I, and S are captured to a large degree in the FBSR solid waste form. The total required control efficiency is achieved by >90-95% capture of these elements in the wet scrubber, and recycling them back to the FBSR.
HCl removal efficiency	≥97%	
HF removal efficiency	≥97%	
Iodine-129 removal efficiency	≥99%	
Particulate capture efficiency	≥99.95%	For final bank of HEPA filters when tested in-situ.
Combined total particulate DF	≥2.0E+8	Estimated minimum combined performance for process gas filter (99%); 90% (wet scrubber); 99% (HEPA prefilters) and 99.95% (HEPAs)

Notes:
1. SO2 emissions, while not regulated under the HWC MACT standards, are expected to be captured in the product and >90% captured in the wet scrubber.
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 2.0E+8.

As Figure 5-2, 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 5-3 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.

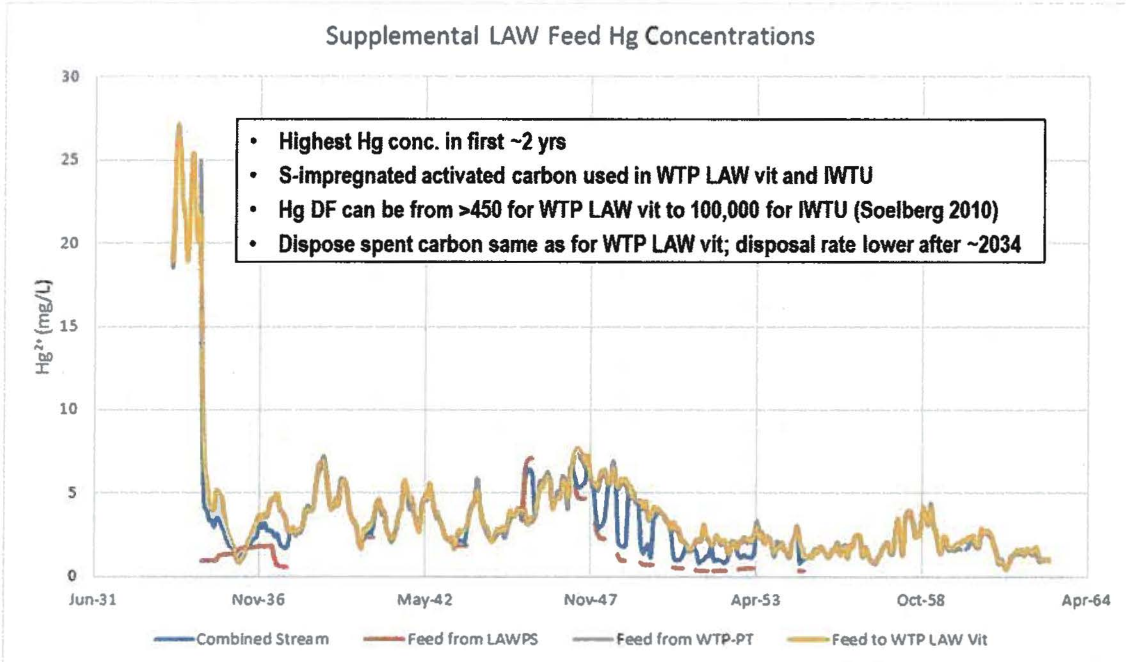


Figure 5-1. Control and disposal of Hg in the FBSR process.

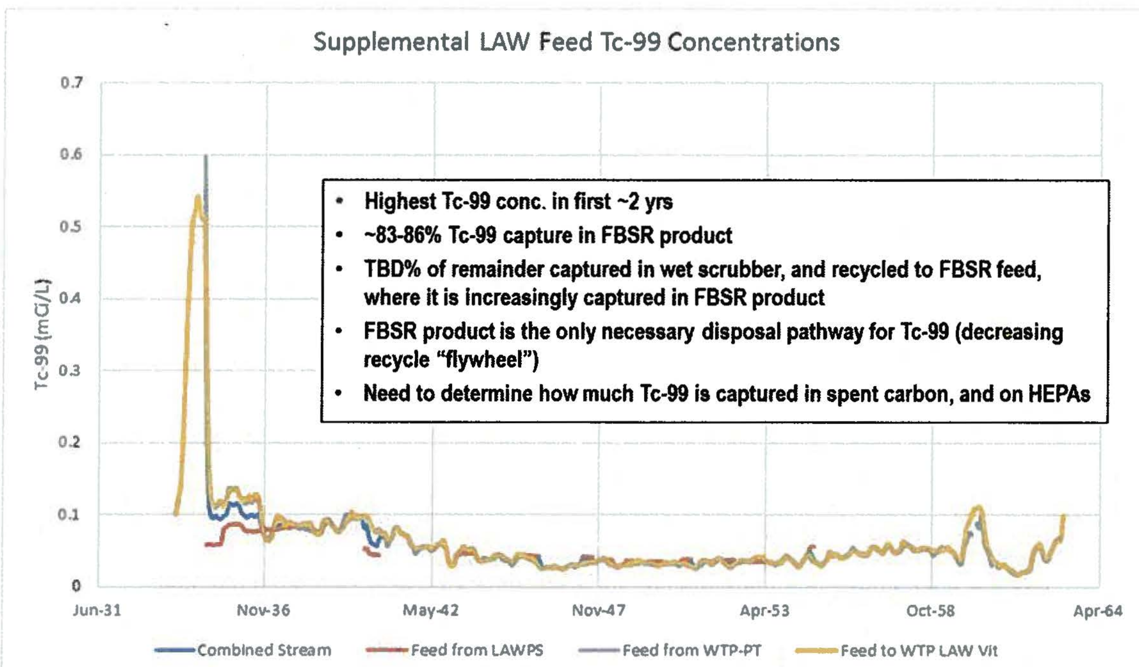


Figure 5-2. Control and disposal of Tc-99 in the FBSR process.

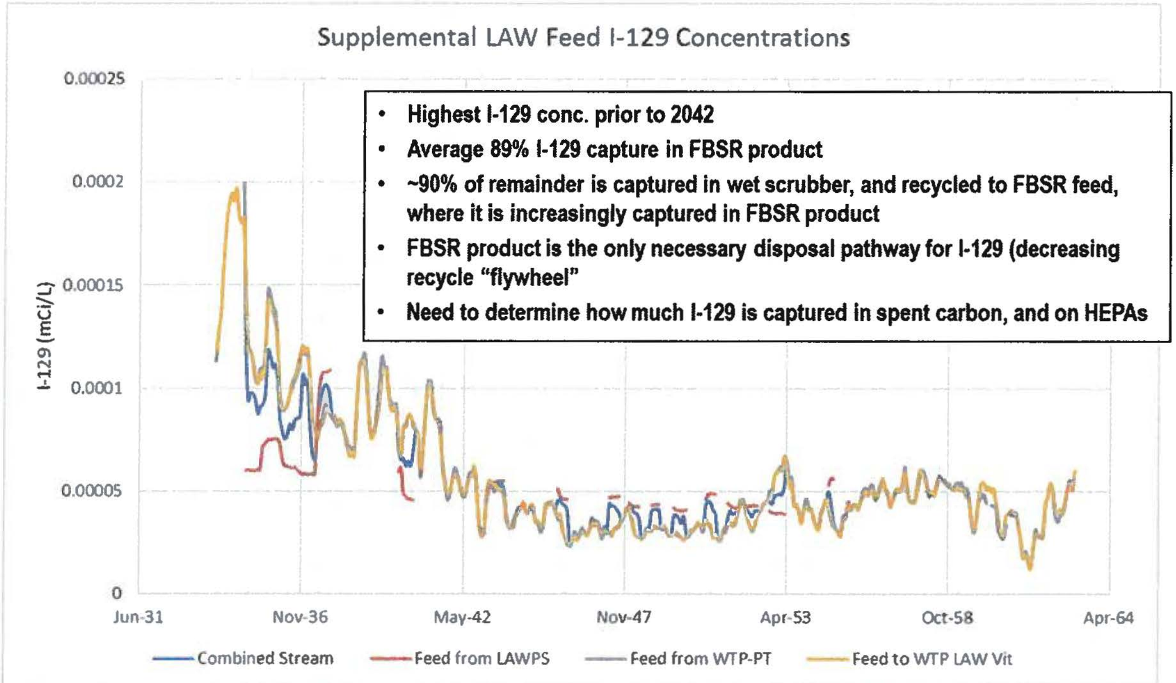


Figure 5-3. Control and disposal of I-129 in the FBSR process.

6. TECHNOLOGY READINESS

Technology Readiness Levels (TRLs) 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 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.

Until the FFRDC team can perform a TRL analysis that is consistent for the technologies under evaluation, it has been recommended to use a broader range of estimating technology readiness by using less quantitative "High, Medium, and Low" indications of technology readiness level. "High" technology readiness may correspond to TRL ~7-9 (full-scale system commissioning); "Medium" may correspond to TRL 4-6 (technology development and demonstration); and "Low" may correspond to TRL 1-3 (basic and feasibility research).

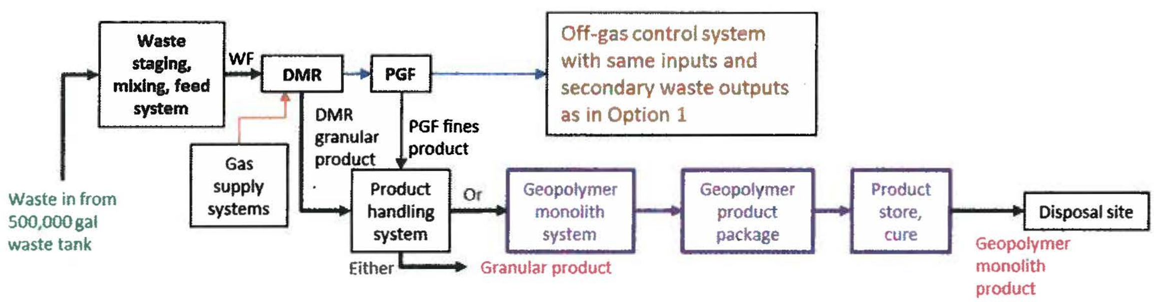
A preliminary draft estimate of these three technology readiness levels is shown in Figure 6-1. A consensus among contributors to the FFRDC Steam Reforming Assessment Area has not been reached, and these relative readiness level estimates may change.

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 are expected to be commercial, mature technologies for full-scale use in various mature industries. These are rated with a High readiness level.

The core DMR, PGF, granular product handling systems, and possibly a wet scrubber for capture and recycle of trace levels of halogens and radionuclides are rated with a Medium readiness level for this particular use for treating Hanford SLAW. While the Studsvik Processing Facility has operated at full scale for many years, the LLW it processes 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, the use is indirect and in many cases not yet demonstrated at a "High" maturity level in that specific use. Likewise, the IWTU, while is 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 "Medium" 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.

Many system and subsystem issues with the IWTU have now been solved; startup/commissioning may soon be complete, and radioactive SBW treatment operations may soon start. 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.

Maturing some components to a High level will still require some technology maturation work. An assessment of costs and schedule to mature all parts of a Hanford SLAW treatment process still needs to be performed by the FFRDC team.



Estimated Technology Readiness Level, assumptions

- Additive, WF systems TRL high
- Gas supply systems TRL high
- Not unique to FBSR, common commercial equipment

- DMR TRL Medium
- Unique to FBSR
- Mineralizing flowsheet TRL Medium
- Coal feed TRL High
- Product system TRL medium

- Geopolymer monolith system TRL Medium
- Unique to FBSR
- Can use common commercial equipment

- Off-gas system TRL high
- Wet scrubber TRL medium
- Not unique to FBSR

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

- Integrated FBSR system TRL is medium 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 6-1. Rough maturity level estimates for the FBSR processing system.

7. 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 Studsvik Processing Facility for LLRW and mixed LLW. 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.
- 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.

8. WORK STILL TO DO

Work that the FFRDC Steam Reforming Assessment Area team needs to still complete includes:

- Refine some details of the FBSR system – feed system, diameter, feed nozzle configuration, filter info, scrubber performance, etc.
- Complete mass balance through product and off gas systems.
- Work with FFRDC team on waste packaging, transport, disposal, cost estimate, TRLs, risks and opportunities, etc.
- Respond to comments and questions.

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Cost Estimate Methodology and Basis
Hanford Supplemental Low Activity Waste Evaluation

Summary

This document lays out preliminary considerations for the estimate development for Supplemental Low Activity Waste (SLAW) which will be 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.

Contents

Acronyms

AACEI	Association for the Advancement of Cost Engineering, International
AoA	Analysis of Alternatives
BDER	Business Decision Estimate Range
DWPF	Defense Waste Processing Facility
EMF	Effluent Management Facility
ETF	Effluent Treatment Facilities
FBSR	Fluid Bed Steam Reforming
I	Iodine
IWTU	Integrated Waste Treatment Unit
LAW	Low Activity Waste
LERF	Liquid Effluent Retention
OPC	Other Project Costs
PRD	Program Requirement Document
ROM	Rough Order of Magnitude
SLAW	Supplemental Low Activity Waste
SRS	Savannah River Site
Tc	Technetium
TEC	Total Estimated Cost Other Project Costs (OPC
WTP	Hanford Waste Treatment and Immobilization Plant

Estimate Purpose

Provide a Rough Order of Magnitude (ROM) Class 5 Planning Estimate for design, construction, life cycle costs including transportation and disposal.

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. Class 5 estimates are prepared using the stochastic or judgement estimating method, using estimating relationships (cost/area or volume, cost/capacity graphs, ratio methods, etc.) or using a direct comparison with similar completed work (adjusted for current conditions).

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.

If time permits, an Estimate Reserve risk analysis can be prepared. However, when a management judgement Estimate Reserve is used, the percentage applied should not be lower than 30%.

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.

Estimate Scope

- Procure Engineering / Design Subcontractor.
- Perform Technology Development activities.
- Perform design, via subcontract, of Facilities for Supplemental LAW including utility and process rooms, sample collection stations, office space, control room as applicable, lag storage feed tanks, lag storage for containers with appropriate containment, truck and or rail unloading / loading facilities.
- Provide design oversight of Engineering / Design Subcontractor for above.
- Procure Nuclear and Criticality Engineering Subcontractor services.
- Procure competitive bid for Construction Subcontractor.
- Construct Supplemental LAW 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.
- Demolition of the Supplemental LAW Facilities at the end of the project.
- Life cycle costs including transportation.
- Costs for electricity and other utilities.
- Operations & Maintenance training costs and Operations & Maintenance staff.
- Truck drivers, rucks and shipping costs.

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.
- Assumes additional Project Management costs during Operations will not be required.
- Project support activities and life cycle costs will be determined via parametric analysis.
- The operations, handling and transport logistics are addressed on an annual basis.
- An escalation rate will be applied uniformly for the capital project and operating costs, consistent with system planning to differentiate Total Discounted (Present Worth) Cost and Actual Cost estimating.

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.

<u>Vitrification</u>
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).

Grout
Saltstone, with defined upgrades and logistics beyond the scope of SRS operations.

Fluid Bed Steam Reforming (FBSR)
Integrated Waste Treatment Unit (IWTU) with alumino silicate product at the Idaho Site.

Estimate Planning
The planning estimates for the proposed SLAW projects will utilize a systems approach for the cost estimate spread sheets based on recent project activities for reference sites for specific ancillary facilities, as applicable.
Pre-processing Facility
New unit operations
Post processing Facility
Balance of Facilities
Control Room

Meetings with the Principle Investigator for the technology being developed for each flow sheet were conducted to develop base cases and alternative options. Scope requirements were discussed as well as challenges and opportunities associated with the proposed process.

A. For the vitrification process, the following facilities are included.
   1. Lag storage capability of 500K gallons
   2. WTP Supplemental LAW Vitrification Facility with 4 melters and off gas systems
   3. WTP Effluent Management with equivalent capability
   4. Balance of Facilities, as required
   5. Lag Storage and Shipping Facility

It is assumed that the existing control room and laboratory could be utilized for this option with minimal impact to normal operations.

Another option for this process would be the use of two (2) melters and off gas systems. For transportation opportunity is to use and rail system for glass container movement to the final storage location.

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 possible use of the laboratory with some shift adjustments could be used for this process.

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

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 possible use of the laboratory with some shift adjustments could be used for this process.

High scope for this process assumes a grout plant is required for each DMR unit to form a monolithic product and that a dedicated control room to support this process.

Work Breakdown Structure
A Work Breakdown Structure has been developed to support spread sheet development as part of this analysis. The estimates presented represent the Total Estimated Cost (TEC), the Other Project Costs (OPC), Operations/ Life Cycle costs, including transportation and Deactivation and Decommissioning Costs.

Tentative WBS Elements are as follows.
01 Project management including project controls
02 Engineering, design, inspection, review, technology development and nuclear criticality safety
03 Project support
04 Procurement
05 Procurement support
06 Field work support by plant forces
07 Construction subcontractor
08 Construction management
09 Construction support
10 Startup and testing
11 Operations, including readiness assessments, startup activities and annual operations and transportation costs
12 Deactivation and Decommissioning

No design has been completed for this process and the estimates are based on flow sheets developed for each base operations and options.

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.

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.

NDAA Study Scope: Feed to be Processed through Supplemental LAW

The requirements for evaluation of Supplemental LAW required by the NDAA did not specify what feed was expected to be processed through Supplemental LAW. In order to provide a common basis for evaluation of the immobilization technologies, the feed to Supplemental LAW is assumed to be the Supplemental LAW feed vector from Revision 2 of the Integrated Flowsheet[1]. The initial evaluation of each flowsheet will utilize the Supplemental LAW feed vector with no modifications. Evaluation of additional pre-treatment will be evaluated, but separately from the immobilization technology unless shown to be needed to make the immobilization technology viable.

Uncertainties

Three major areas of uncertainty have been identified that impact the evaluation of immobilization technology for Supplemental LAW.

1.0 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[2] as well as the impacts of a 20% variation for selected components on the baseline process[3]. The evaluation of uncertainty determined that 20% is not a bounding value for the BBI uncertainty, even for major analytes.

Second, the feed vector provided from the Integrated Flowsheet is based on proposed processing for retrievals and facility startup times 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[4].

Third, the TOPSim model used to generate the feed vector has many simplifications[5]. 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[6]. 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.

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 and 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.

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.

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)[1]. 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. 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 missions scale or duration increased.

3. IDF Performance Assessment

The performance assessment (PA) for the Integrate 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. *The discussion of analytical approach contains further details.*

Additional items will be added as identified during evaluation.

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.

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 should identify when the feed vector would result in an immobilized product outside the bounds of previous testing and address the impact on the viability of that technology.

The most significant challenges exist in developing cost estimates for each technology. 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 is discussed in the discussion on cost estimation.*

Additional items will be added as identified during evaluation.

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