Independent Analysis of Alternatives for Disposition of the Idaho Calcined High-Level Waste Inventory

Volume 1 - Summary Report

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APPROVALS

Joel T. Case
AoA Team Lead DOE-ID

4/13/2016
Date

Hoyt C. Johnson
AoA Team Lead DOE-EM

3-30-2016
Date

Thomas M. Brouns
AoA Team Member

4/5/2016
Date

John E. Marra
AoA Team Member

4/5/16
Date

Jay A. Roach
AoA Team Member

3/30/2016
Date

Patricia C. Suggs
AoA Team Member

30 March 2016
Date

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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	Analysis of Alternatives
BSG	borosilicate glass
CBPC	chemically bonded phosphate ceramics
CCIM	cold crucible induction melter
CDP	Calcine Disposition Project
CSSF	Calcine Solids Storage Facility
DBH	deep borehole
DOE	U.S. Department of Energy
DWPF	Defense Waste Processing Facility
EIS	Environmental Impact Statement
EM	Office of Environmental Management
GAO	Government Accountability Office
GFC	glass-forming chemical
HIP	hot isostatic press
HIPing	hot isostatic pressing
HLW	high-level waste
ICP	Idaho Cleanup Project
INL	Idaho National Laboratory
IPG	iron phosphate glass
IWTU	Idaho Waste Treatment Unit
JHCM	Joule-heated ceramic-lined melter
LCC	lifecycle cost
MAR	material at risk
RCRA	Resource Conservation and Recovery Act
ROD	Record of Decision
SBW	sodium-bearing waste
SNF	spent nuclear fuel
SRS	Savannah River Site
SSCs	structures, systems, and components
TRA	technology readiness assessment
TRU	transuranic
UNF	used nuclear fuel
WAPS	Waste Acceptance Product Specification
WASRD	Waste Acceptance Systems Requirements Document
WIPP	Waste Isolation Pilot Plant
WTP	Waste Treatment and Immobilization Plant

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1. BACKGROUND

The U.S. Department of Energy (DOE) Idaho Field Office and the Office of Environmental Management (EM) chartered an independent Analysis of Alternatives (AoA) for the Idaho Calcine Disposition Project (CDP), which is part of the overall Idaho Cleanup Project (ICP). The Charge Memorandum authorizing this AoA is provided in Appendix A of *Volume 2 – Detailed Report*.

The scope of the CDP includes the design and construction of a capability (i.e., facility and ancillary systems) for retrieval and processing of approximately 4,400 m^3 of calcine for final disposition in a geologic repository located outside the state of Idaho. Calcine, which is a dry, granular material produced in a fluidized bed calcination process, is stored in six underground storage facilities referred to as Calcine Solids Storage Facilities (CSSFs).

The current CDP proposed path forward is to pneumatically retrieve the calcine from the CSSFs and transfer it to the Idaho Waste Treatment Unit (IWTU) for processing.[1] There it will be blended with additives and processed in a hot isostatic pressing (HIPing) system to immobilize the material. The HIPing process was identified as the preferred calcine treatment technology by DOE through the *National Environmental Policy Act* process, and documented in the resulting High-Level Waste (HLW) Environmental Impact Statement (EIS) Amended Record of Decision (ROD), issued December 2009.[2] As envisioned, the HIPing process will produce a glass-ceramic waste form deemed suitable for disposition of HLW in a geologic repository, although the waste form has not been qualified yet for this specific application.

The AoA was chartered for two primary reasons: 1) a new requirement was issued by the Secretary of Energy for all projects exceeding $10M in total cost to conduct an AoA, independent of the contractor, prior to approval of Critical Decision 1,[3,4] and 2) the current baseline to immobilize the calcine via HIPing is technically immature, with significant challenges to overcome, which may represent unacceptable project risk. An important factor in the original selection of HIPing was its ability to provide the lowest volume of final waste, while producing a robust waste form. At the time of the prior analyses, the Yucca Mountain disposal facility was the assumed disposal path and the associated disposal cost per canister (i.e., 2 feet diameter by 10 feet long) was estimated at $620,000.[5] Currently, a preferred disposal option for DOE HLW has not been identified, and other options are being evaluated. Thus, the assumptions regarding disposal costs, and drivers to reduce the waste form volume, may no longer be valid. Consequently, the uncertainty of the disposition path, and related final waste form requirements, resulted in an additional variable that had to be accounted for during the AoA. Both processing and

[1] The IWTU will require decontamination and decommissioning of existing process vessels and equipment following sodium-bearing waste (SBW) treatment, as well as significant modifications (e.g., an addition must be constructed that increases the facility footprint by ~60%).
[2] Amended Record of Decision: Idaho High-Level Waste and Facilities Disposition Final Environmental Impact Statement; Correction, *Federal Register*, U.S. DOE, Washington, DC, pp. 1615–1616, January 12, 2010.
[3] *Memorandum for Heads of All Department Elements*, from Secretary Moniz, issued on December 1, 2014.
[4] *Memorandum for Heads of All Department Elements*, from Secretary Moniz, issued on June 8, 2015.
[5] *Mission Need Statement: Calcine Disposition Project, Major Systems Acquisition Project*, DOE/ID-11252, U.S. Department of Energy, Washington, DC, January 2007.

disposal options were considered, separately, and in various combinations, as described in more detail below.

2. APPROACH

The AoA was performed in four steps: 1) all potentially viable processing and disposal options were identified through review of the Idaho National Laboratory (INL) EIS,[6] prior studies,[7] and new potential alternatives and considerations, particularly those related to disposal options; 2) an initial pre-screening was conducted for general process technology categories, followed by 3) a detailed screening of the remaining processing options, which included variants within each processing category, combined with the identified disposal options; and finally 4) a detailed analysis of the remaining alternatives was performed, which included the cost estimates.

Identification of the processing and disposal options resulted in the general starting point of this AoA, which is depicted in Figure 1. This figure shows the processing categories and disposal options evaluated as part of the complete AoA, including long-term storage and offsite treatment strategies. Note that during the pre-screening step, only the processing options were considered. The disposal options and other disposition strategies, which were assessed during the detailed screening and analysis steps, are shown on the diagram for completeness.

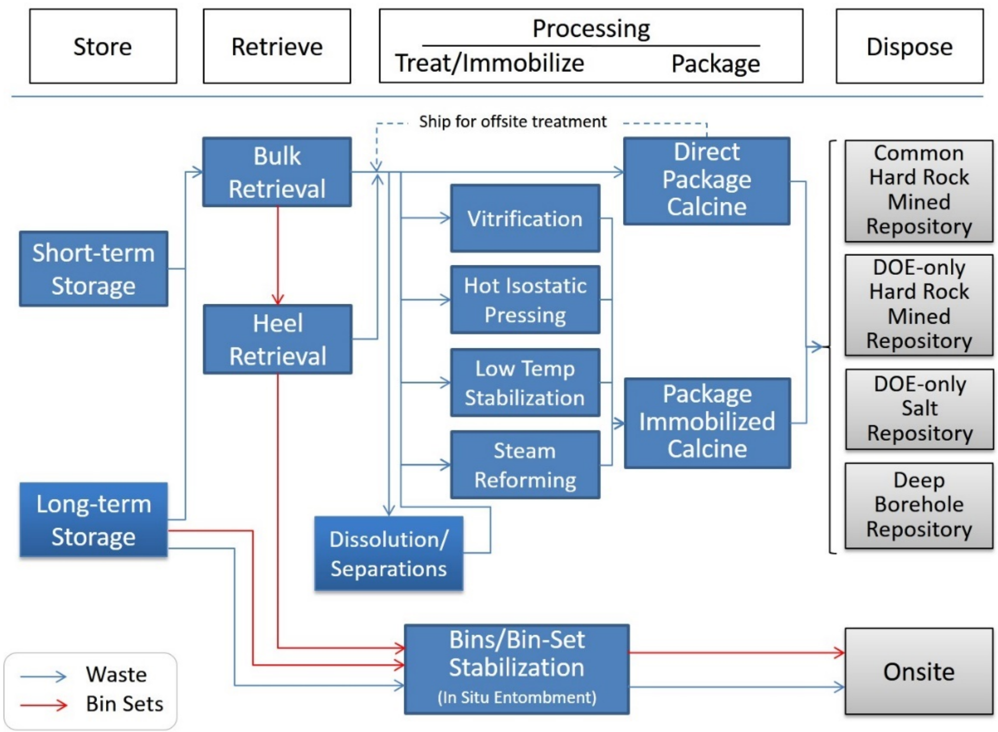

Figure 1. Flow diagram of overall calcine disposition options, and specific processing and disposal alternatives considered in this AoA *(Note: "Ship to offsite treatment" can branch to any of the dissolution/processing options shown).*

[6] *Idaho High-Level Waste and Facilities Disposition Final Environmental Impact Statement*, DOE/EIS-0287, U.S. Department of Energy, Washington, DC, September 2002.

[7] *Idaho Cleanup Project, Calcine Disposition Project Calcine Treatment Options Summary*, RPT-650, Rev. 0, September 2009, and Krahn, S.L., et al., *CRESP Independent Review of Calcine Disposition Project (CDP) Processing Options and Plans*, August 2011.

The detailed screening and analysis steps were conducted using weighted, multi-attribute criteria to comparatively evaluate the identified processing and disposal options. The "Best Practices" for conducting AoAs identified by the Government Accountability Office (GAO)[8] were considered and implemented, as applicable. Details of the methodology used are documented in the Review Plan.

The only departure from the GAO Best Practices is related to the use of total lifecycle cost (LCC). First, while a retrieval technology/system has been investigated, cost data for a variety of retrieval options is not available, and the actual retrieval system has not been determined. Consequently, this component of the total cost. as used for purposes of this AoA, was based on a single proposed pneumatic retrieval system and may not represent the actual retrieval system implemented. Thus, this represents increased uncertainty in defining a total LCC. Nevertheless, because all options considered during the detailed analysis step require retrieval, it was determined that this element would not be a discriminator during evaluation of the alternatives. Additionally, the disposal path will have a major impact on processing and final waste form requirements, and consequently on the LCC. Because the disposal strategy and related costs are unknown at this time, the disposal component of the total cost presented for each option was not included in this AoA. Rather, criteria were used in the detailed screening and analysis steps that specifically consider overall disposal volumes and disposal efficiencies associated with each of the processing/disposal option combinations. This provided a basis for conducting a relative comparison of the alternatives without giving preference to alternatives based solely on final waste form volume.

3. PROCESSING AND DISPOSAL OPTION DESCRIPTIONS

A broad variety of processing and disposal options were considered during this AoA. For each of the process categories considered, variants were identified, as applicable, during the detailed analysis steps. Two variants were considered relevant to all processing options: 1) long-term storage (e.g., 100 years; longer-term storage was not considered feasible) prior to any action, and 2) direct packaging for offsite treatment. The long-term storage option was not specifically included in the pre-screening step because it will not affect the processing systems, while the direct packing for offsite treatment option will. The processing and disposal options are briefly described in Sections 3.2 and 3.3, respectively. Retrieval is common to all processing options, with the exception of In Situ Entombment. Accordingly, it is described separately in the following section.

3.1 Retrieval

A brief discussion of calcine retrieval is warranted as it is critical prerequisite to all processing options and represents key technical challenges for the CDP. Consequently, the retrieval activity was not considered a discriminator during the AoA for any option resulting in offsite disposal.

It is presumed that the calcine can be transferred out of the bins using a pneumatic vacuum/transfer technology similar to the approach by which it was originally emplaced. This is a common and large-scale technique routinely used commercially for dry particulate solids (e.g., grain storage and transfer). The approach has been tested for the calcine retrieval application and successfully demonstrated on surrogate materials.[9] As a result, a pre-conceptual design has been developed based on this technology.

[8] *DOE and NNSA Project Management – Analysis of Alternatives Could be Improved by Incorporating Best Practices*, GAO-15-37, Government Accountability Office, Washington, DC, December 2014.

[9] See *Calcine Bins Retrieval and Transfer System: Test Report*, 215-6-004, AEA Technology Engineering Services, Inc., Mooresville, NC, January 2005, and *Calcine Bins Retrieval and Transfer System Enhancements: Test Report*, 2200-4-001, AEA Technology Engineering Services, Inc., Mooresville, NC, April 2006.

Key challenges related to retrieval include the following:

- The size and number of access risers available for retrieval operations varies by bin. Additionally, the configuration of each binset requiring retrieval is different.
- Clumping/caking of the calcine is expected, but is assumed to be a manageable problem. An exception would be extreme caking, resulting, for example, from large amounts of water entering a bin or sintered bonding due to the temperature and pressure environment over time.
- The actual characteristics of the as-retrieved calcine will be uncertain due to differing chemical and physical properties, coupled with commingling during emplacement and retrieval.

The access challenges can likely be resolved through equipment development and testing. The retrieval activities also provide an opportunity to better understand the physical and chemical characteristics of retrieved calcine. This is important in the context of processing and waste form requirements. Until a disposal path is defined, and the related waste form/processing requirements determined, development of the most effective retrieval technology/system could proceed independently since it is a common need to virtually all processing options (see *Recommendations* in Section 6 of this report).

3.2 Processing Options Considered

The AoA team considered a broad range of processing categories, with multiple variants within several of those categories. These are summarized below.

Package for Direct Disposal
Prior to the current ROD, this processing option represented the baseline for calcine disposition. In this alternative, the calcine will be retrieved and transferred to receipt tanks within the IWTU facility and subsequently transferred into disposal canisters. The current design of the IWTU was based on this disposition option, so minimal facility modifications would be required to implement the approach. In general, this option would be the least sensitive to fluctuations in calcine chemical, radiological, and physical characteristics because an immobilized waste form, such as glass or ceramic, is not produced. Additionally, mixing and/or heating, which result in potential airborne particulate and offgas aerosols, are not employed. Thus, these potential contaminants do not require the added processing and management associated with other processing options. This option is also amenable to virtually any disposal canister configuration, ranging from a standard spent nuclear fuel (SNF)/glass canister design (i.e., nominal 2 feet diameter by 10 or 15 feet long),[10] to the proposed universal canister design for deep borehole disposal (i.e., nominal 1foot diameter by 15 feet long),[11,12] to the proposed large-volume HLW canister (i.e., nominal 5.5 feet diameter by 17.5 feet long), which was developed specifically for this application.[6]

[10] Hill, T.J., et al., *Canister Design for Direct Disposal of HLW Calcine Disposal Produced at the Idaho National Engineering and Environmental Laboratory*, WM-4521, Waste Management Proceedings, Tucson, AZ, March 2004.

[11] Arnold, B.W., et al., *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2011-6749, Sandia National Laboratories, Albuquerque, NM, October 2011.

[12] Larger diameter boreholes that would accommodate 20-inch casing have been proposed, allowing emplacement of 18-inch diameter waste packages, essentially reducing the number of required boreholes by 50%. Beswick, A. J., F. G. F Gibb, and K. P. Kravis. 2014. *Deep borehole disposal of nuclear waste: engineering challenges*. Proceedings of the Institution of Civil Engineers, 167, EN12. p.47-66.

The key challenges facing the direct package for disposal option are related to regulatory concerns. For disposal options that are expected to require robust waste form performance, such as a hard rock mined repository, it will be challenging to gain acceptance for direct disposal of the as-retrieved calcine, which contains hazardous constituents that are regulated under the *Resource Conservation and Recovery Act* (RCRA). This concern was a factor in the decision to established HIPing as the current baseline, as documented in the amended ROD of 2009. Conversely, this disposition strategy is assumed to be more readily acceptable for disposal options that may offer more flexibility in final waste form, such as mined salt, or deep borehole repositories, with DOE-only waste. For these disposal options, a "No-Migration" variance from the EPA is assumed to feasible based on the Department's experience with the Waste Isolation Pilot Plant (WIPP) facility in New Mexico.

Package for Offsite Treatment

This alternative was initially assumed to be applicable to all feasible processing options, but after further consideration, the AoA team determined that construction of a new facility for offsite processing offers no advantages over construction of an onsite processing facility. Accordingly, the only existing viable offsite processing option is vitrification, either at the Savannah River Site (SRS) Defense Waste Processing Facility (DWPF) or the planned Waste Treatment and Immobilization Plant (WTP) at Hanford. Consequently, the most likely waste form is a borosilicate glass (BSG), which is the basis for these facilities. However, BSG is not necessarily an efficient chemistry for calcine (see discussion of vitrification options in the following section). Introducing the calcine powder into the processing stream at either of these facilities will require significant modification to the feed preparation system within these plants to either create a slurry to accommodate current designs or enable dry feed to the melter systems. Adding dispersible powders to the operating vitrification plants, which are designed to manage wet slurries only, will also introduce new hazards that may significantly affect existing safety bases. Nevertheless, this option is assumed to be less costly than establishing a new processing capability onsite. Future offsite processing options may be identified for the retrieved calcine, but none were specifically identified that are appropriate for this application.

Offsite processing options would also increase safety risks because this disposition strategy will require multiple shipments and related handling. At a minimum, the calcine would have to be 1) packaged, loaded, and shipped from Idaho to the treatment facility; 2) unloaded, transferred into a feed system, processed, and packaged; and 3) loaded and transported from the treatment facility to the disposal facility. Safety during transportation represents a significant contribution to overall risk, and this option would substantially increase transportation activities.

Vitrification

In the context of radioactive waste immobilization, vitrification is the process by which glass forming chemicals (GFCs) or glass frit are combined with waste material and introduced into a vessel, either as a dry powder or slurry, which is heated in the vessel to an appropriate temperature such that a glass, glass-ceramic, or other glass-like product is formed. Several technologies can perform this process, and the efficacy of a specific technology depends on the application.

Two primary categories of vitrification technologies have been investigated and/or implemented for radioactive waste immobilization: 1) melters that use energized electrodes within the melt pool as the heat-generating energy source, often referred to as Joule-heated ceramic-lined melters (JHCMs); and 2) inductively heated melters that use an energized external coil to produce an electromagnetic field, which in turn provides the heat-generating energy source (e.g., cold crucible induction melters [CCIMs]). Multiple variants exist within each of these two broad categories, including in-can batch and continuous processes. These were all considered during the AoA. However, the two most promising include the conventional JHCM and CCIM, which were considered during the detailed analysis.

Joule Heated Ceramic-Lined Melters – The conventional JHCM is the baseline HLW vitrification technology in the U.S. It has been deployed in the SRS DWPF and the West Valley Demonstration Project, and is planned for implementation in the WTP facility for both HLW and low-activity waste inventories. The JHCMs are limited to operate between 1,150°C and 1,200°C, due to the refractory that is in contact with the molten glass, are generally designed to produce an amorphous borosilicate glass waste form, and are not amenable to crystalline waste forms that exhibit high viscosity at these temperatures. While waste loadings comparable to current DWPF performance of 30wt% to 35wt% are estimated for some of the calcine, it is not clear how this will be achieved without the ability to conduct batch characterization such that glass formulations can be optimized and validated. Limitations of some operational parameters for JHCMs (e.g., temperature, glass viscosity, crystalline phases) can result in relatively inefficient processing for significant portions of the calcine inventory due to its chemistry. For example, approximately 40% of the calcine inventory, primarily the high cadmium zirconia calcine, is expected to achieve much lower waste loadings (i.e., 20wt% to 25wt%) to ensure an acceptable waste form, although this limitation is highly dependent on the disposal option. Crystalline-tolerant glass formulations may improve waste loading, but these compositions would be more sensitive to the feed chemistry. Additionally, glass compositions that offer waste loading benefits, such as iron phosphate glass (IPG), present new challenges since the chemistry of the melt pool is aggressive and accelerates degradation of the immersed electrodes.

Cold Crucible Induction Melters – The second key variant considered was the CCIM technology. CCIM systems use relatively high-frequency generators (i.e., 250 kHz to >5 MHz) to produce a current that is passed through an induction coil surrounding a segmented crucible with cooled walls. Typically, water is used to cool the walls, but other media such as steam or a gas can be used, depending on the design of the system. The specific geometry and configuration of the crucible walls and bottom, as well as the glass draining system, feed system interface, and offgas system interface designs, are flexible and can be optimized for processing a specific material (i.e., dry or slurry), or be designed to allow processing of a broader range of materials. As a result, CCIMs achieve melt pools much faster and exhibit much higher specific glass production rates compared to JHCMs.

Because the walls and bottom of the crucible are cooled, a solidified layer of glass forms along these surfaces, which protects the materials of construction from the molten glass. In general, CCIMs have more flexibility in glass/melt pool chemistry, crystal tolerance, and operational temperature, which results in higher waste loadings for a given waste chemistry (e.g., both IPG and BSG compositions can be processed with a relative increase in waste loadings ranging from over 20% to 170%).[13,14] While CCIMs have been deployed in several countries for processing radioactive waste streams (i.e., France, Russia, and Korea), it is relatively immature for U.S. applications.

Another key limitation of the CCIM technology is scale-up. While the specific production rate is higher than that of the JHCMs, the largest CCIM ever constructed and demonstrated (limited) was a 1.4-m-diameter system by Areva,[15] although CCIMs measuring 1.2 m diameter have been used in commercial glass production applications for many years. However, this range (i.e., 1.4 to 1.8 m) may be

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[13] Marra J.C., and Kim, D.-S., *Towards increased waste loading in high level waste glasses: developing a better understanding of crystallization behavior*, 2nd International Summer School on Nuclear Waste Glass Waste Form: Structure, Properties, and Long-Term Behavior, SumGLASS 2013, Procedia Materials Science 7 (2014)87-92.
[14] Smith G.L., et al., *Silicate Based Glass Formulations for Immobilization of U.S. Defense Wastes Using Cold Crucible Induction Melters*, PNNL-23288, EMSP-RPT-021, Rev. 0.0, Pacific Northwest National Laboratory, Richland, WA, May 2014.
[15] Do Quong, R., et al., *Integrated Pilot Plant for a Large Cold Crucible Induction Melter*, Waste Management Conference Proceedings 2002, Tucson, AZ, February 24-28, 2002.

near the theoretical maximum diameter for a CCIM with simple right circular cylinder geometry; thus, multiple units would likely be required for the CDP application.

Hot Isostatic Pressing

The AoA considered two key variants of HIPing: 1) direct HIPing, which uses no additives, but compresses the calcine to theoretical density for significant volume reduction (i.e., 50%); and 2) HIPing with additives to produce a glass-ceramic referred to as Synroc, which is the current CDP baseline. In either case, the technology consists of a pressure vessel surrounding an insulated, resistance-heated furnace. The process of HIPing radioactive calcine involves a stainless steel can that is filled with the feed material, which is then evacuated through a bake-out process of 400°C to 500°C, over about 5 hours. During bake-out, a vacuum is established on the HIP can, and any offgas is routed through filters, including in-cell filters and traps, to remove any particulates or gaseous components (e.g., mercury is captured and amalgamated). The can is then sealed and placed into the HIP furnace, and the vessel is closed, heated, and pressurized. The nominal operating temperature is 1,150°C and the pressure is 15,000 psi. These conditions are held for about 2.5 hours. The pressure is applied isostatically via argon gas, which at pressure is also an efficient conductor of heat.

The combined effect of heat and pressure consolidates and immobilizes the waste into a dense, monolithic block sealed within the can. After the HIPing process is complete, the HIP can is cooled within the HIP vessel to a temperature sufficient for removal. The argon used during the HIP process is filtered and stored in a manner that conserves both argon and invested pressure.

The baseline HIPing process produces Synroc-C made from several natural minerals that together incorporate nearly all of the elements present in HLW calcine into their crystal structures. The main minerals in Synroc-C are titanates that include hollandite ($BaAl_2Ti_6O_{16}$), zirconolite ($CaZrTi_2O_7$), and perovskite ($CaTiO_3$). Zirconolite and perovskite are the major hosts for long-lived actinides, such as plutonium, though perovskite is principally for strontium and barium. Hollandite principally immobilizes cesium, along with potassium, rubidium, and barium. In general, while producing a very robust waste form, due to the combined pressure and temperature levels, HIPing is assumed to represent the greatest safety risk of all the processing options considered during the AoA.

Low-Temperature Stabilization

Stabilization and solidification are techniques used to reduce leachability from a hazardous or radioactive waste through physical and chemical means. In the context of this assessment, “low-temperature stabilization” refers to a variety of non-thermal stabilization and solidification approaches for chemical immobilization, macro-encapsulation, and/or micro-encapsulation of radioactive and hazardous waste to produce a waste form with improved contaminant release properties (e.g., Toxicity Characteristic Leaching Procedure for RCRA metals), no free-liquids, and/or reduced risk of dispersing fine particulate by creating a monolithic waste form. Cementitious waste forms (a.k.a. hydro-ceramics) are the most widely adopted form of low-temperature stabilization, and are used extensively in low-level radioactive waste management, as well as intermediate-level waste management internationally. Other low-temperature processes include polymer stabilization, low-temperature glass-ceramic stabilization such as the magnesium phosphate-based Ceramicrete waste form (referred to as chemically bonded phosphate ceramics [CBPC]), and others.[16] A low-temperature stabilization option—direct cementation—was considered in the INL HLW EIS[17] for calcine and sodium-bearing waste (SBW) disposition. As a result, it

[16] Spence, R., and Shi, C., *Stabilization and Solidification of Radioactive and Mixed Waste*. Boca Raton, Florida: CRC Press, 2005.
[17] *Idaho High-Level Waste and Facilities Disposition Final Environmental Impact Statement*, DOE/EIS-0287, U.S. Department of Energy, Washington, DC, September 2002.

was reevaluated as part of this AoA to determine if significant advances in the technology had occurred since that time.

Two primary low-temperature stabilization options were considered most viable for INL calcine disposition in this AoA: 1) cement or grout waste form similar to the SRS saltstone, which consists of Portland cement, blast furnace slag, fly ash, solid or liquid radioactive waste, and other additives; and 2) a CBPC waste form that requires similar processing as grout, but produces a potentially more durable waste form with higher waste loading, although at greater cost.

Cement/Grout – Although relatively inexpensive to implement and technically mature, this saltstone-like process would likely result in the highest final waste form volume, increasing the initial volume by 3 to 4 times. Thus, storage, transportation, and disposal costs may be prohibitive. Additionally, for any repository with a strong reliance on the long-term performance of engineered barriers, especially metal waste packages, grout waste forms can negatively impact local pH, resulting in accelerated degradation of these engineered barriers.

Chemically Bonded Phosphate Ceramics – The CBPC stabilization process, including composition development, is relatively immature. However, cursory investigation indicates that much higher waste loadings could be achieved compared to cement/grout. For some calcine chemistries, waste loadings similar to IPG composition may be achievable. In the past, the raw materials for conducting large scale CBPC processing were not readily available. However, over that past ten years these materials have become much more available due to commercialization for novel applications. In general, the raw materials for CBPC products are about five times greater than conventional Portland cement-based grouts.[18,19] However, the increased waste loadings and resulting reduced waste volume are expected to offset those increases when life cycle costs are considered (e.g., packaging, transportation, and disposal costs). The waste form is also much more durable, leach resistant product.

Steam Reforming[20]

Steam reforming, in the context of radioactive waste treatment, is a fluidized bed process that uses energy from high temperature (superheated) steam to create an oxygen deficient reaction between water and a hydrocarbon to form hydrogen gas and carbon dioxide (i.e., pyrolysis). Steam reforming has been used on a large scale by the petrochemical industry to produce hydrogen for many decades.

Studsvik commercialized a fluidized bed steam reforming (FBSR) technology based on a process known as THermal Organic Reduction (THOR®) for processing radioactive wastes. The THOR® FBSR process is the basis for the FBSR system installed in IWTU for treating the SBW. A typical THOR® FBSR process can use either a single reformer or dual reformer. The dual reformer flowsheet, which is only needed if the waste being processed contains organics that need to be destroyed, is the design implemented in IWTU. The dual reformer consists of the following primary subsystems: 1. A feed for gases, liquids, slurries, and co-additives such as clay and denitration catalysts; 2. The fluidized bed reactor vessel known as the Denitration and Mineralization Reformer (DMR) 3. A high temperature filter

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[18] Swanson, G., *Building Biology Based New Building Protocol, Magnesium Oxide, Magnesium Chloride, and Phosphate-base Cements*, available at www.geoswan.com, or contact the author at 512-288-9097.

[19] Wagh, A.S., *Chemically Bonded Phosphate Ceramics – Twenty-First Century Materials with Diverse Applications*, Elsevier Publishing, 2004, ISBN: 0-08-044505-5.

[20] The following discussion is adapted from James J. Neeway, Nikolla P. Qafoku, Joseph H. Westsik Jr. & Christopher F. Brown, Carol M. Jantzen, Eric M. Pierce. (2012) Radionuclide and contaminant immobilization in the fluidized bed steam reforming waste product. Radioactive Waste, Rehab Abdel Rahman (Ed.). ISBN: 978-953-51-0551-0, InTech, Available from: http://www.intechopen.com/books/radioactive-waste/radionuclide-and-contaminantimmobilization-in-the-fluidized-bed-steam-reforming-waste-products.

(HTF) to catch fines and recycle them to the DMR bed to act as seeds for particle size growth; 4. The solid and product collection from the DMR and HTF; 5. The off-gas treatment, which includes the second reformer known as the Carbon Reduction Reformer (CRR); and 6. The monitoring and control systems.

The key FBSR reactions occur in the DMR. The bed is fluidized with superheated steam and near-ambient pressure. Granular carbon is also fed into the bed as a fuel/energy source and reducing/ denitration agent. When the waste feed is introduced into the fluidized bed as fine spray, the waste feed reacts to form new minerals after contacting the heated fluidized bed. Nitrates and nitrites in the feed react with reductive gases to produce mainly nitrogen gas with traces of NOx. The nonvolatile contaminant constituents, such as metals and radionuclides, are immobilized by being incorporated into the final mineral species in the granular bed product. The granular products are removed from the bottom of the DMR and finer product solids are separated from the process outlet gases by the HTF. The finer HTF mineral solids can be recycled back to the DMR bed as seed material to the DMR bed. The process gases exit the DMR through the HTF and consist mainly of steam, N_2, CO, CO_2, and H_2. Some low levels of NO_X, acid gases, and short-chained organics may also be present and these can be destroyed in the CRR. The exiting process outlet gases are treated in the other components of the off-gas system to meet air permit emission limits.

Application of the FBSR process to calcine could be accomplished using the existing system within IWTU, although a simpler flowsheet would be likely (i.e., no CRR) since the calcine has already had the NO_x removed in prior processing. However, since the calcine is in a solid granular form, it would have to be dissolved as a pretreatment step prior to FBSR processing. The IWTU facility does not have the capacity to perform this step, so a new annex or separate facility would likely be required.

Long-Term Storage

Long-term storage was considered as a variant to all processing options. This approach would provide interim decay storage (i.e., 100 years or less)[21] of the calcine within the binsets prior to retrieval and processing. Decay storage will reduce the overall level of radioactivity, and may help to reduce the amount of material at risk (MAR), such that a lower facility hazard category could be achieved. As a result, for the future processing facility, it may result in fewer safety-related systems, thus offering programmatic benefits (i.e., LCC, schedule, risk reductions). However, it may also make retrieval more difficult due to continued compaction and potential agglomeration of the calcined solids within the CSSF binsets.

3.3 Disposal Options Considered

The AoA team initially identified five disposal options: 1) in-place entombment, 2) commingled mined hard rock, 3) DOE-only mined hard rock, 4) DOE-only mined salt, and 5) DOE-only deep borehole repositories. These are briefly summarized below.

Common Mined Hard Rock Disposal

The U.S. reference geologic repository at Yucca Mountain was based on the plan for combining commercial spent/used nuclear fuel (SNF/UNF) and HLW with defense HLW and other DOE-managed waste in a single repository. The decision that separate commercial and defense repositories were not needed was made in 1985, as required by the *Nuclear Waste Policy Act* (NWPA)[22], following a DOE

[21] Extended storage periods (e.g., 300 years or more) are known to positively affect MAR, but will likely never be accepted by stakeholders or regulators, and were not considered feasible.
[22] 42 U.S.C. 10101, Nuclear Waste Policy Act of 1982, as amended, Public Law 97-425, 96 Stat. 2201, January 7, 1983.

review that concluded that cost efficiency was the only differentiator of six statutory factors considered. At that time, it was concluded that a common repository could cost less than developing separate facilities for defense and commercial HLW.[23] The Yucca Mountain repository was also designed around a hard rock disposal environment, specifically volcanic tuff, in which migration from the unsaturated zone of the repository into an underlying aquifer (saturated zone) would result in an all-pathways dose to a member of the public of less than the regulatory limit of 15 mrem/year.

For the AoA, this scenario assumes that a common repository is established with similar characteristics to those for the U.S. reference repository at Yucca Mountain. Therefore, the AoA assumed the following:

- The repository will have the same regulatory framework as Yucca Mountain, with the same or equivalent requirements to the current Waste Acceptance Systems Requirements Document (WASRD), and DOE-EM Waste Acceptance Product Specification (WAPS) for vitrified HLW, representing more-stringent requirements for waste form characteristics and performance than many other disposal options.
- Waste canisters would be of similar construction, dimension, and sealing as those currently in use or planned for future DOE-EM HLW processing facilities.
- Changes to the current WAPS to allow for different waste form characteristics would be possible, but would require qualification, review, and approval similar to that historically implemented for waste destined for Yucca Mountain.
- RCRA-regulated hazardous waste would not be acceptable for disposal at the repository without approved treatment to remove the hazardous characteristics and/or delisting.

Based on these assumptions, the precedent set by the regulatory framework established for the Yucca Mountain facility, as a repository for both commercial and DOE waste, likely represents the most challenging disposal option for which to obtain acceptance of alternate waste forms. Demonstrating equivalent durability and performance of ceramic, IPG, or crystalline tolerant silicate glasses is expected to be achievable with additional waste form validation testing, coupled with development and acceptance of tailored degradation testing protocol. On the other hand, gaining acceptance for direct disposal of packages containing untreated calcine represents a significant increase in effort related to performance assessment modeling and prediction, with increase overall risk. However, the potential cost and schedule benefits savings, as well as technical risk reduction related to processing and transportation (i.e., lowest volume of waste to be disposed for all options), may justify this increased investment of resources.

DOE-Only Mined Hard Rock Disposal

This disposal option is similar to the common repository option, described above, but it is assumed to include only DOE HLW and SNF. The geology and general configuration are assumed to be similar to the Yucca Mountain design, as would be the waste acceptance criteria (i.e., WASRD and WAPS). However, because it would contain only DOE wastes, the AoA team assumed that obtaining acceptance for new waste forms (e.g., non-BSG) would be more likely, and generally lower risk, as compared to a common repository. This is assumed valid, in part, because some restrictions included in the Yucca Mountain-specific acceptance criteria, (e.g., plutonium limits per package, wattage limits) may not be applicable to another type of hard rock mined repository. Additionally, precedent set by the Department's experience with establishing WIPP indicates that more flexible may be available for a DOE-only disposal facility. In

[23] *Report on Separate Disposal of Defense High Level Radioactive Waste*, U.S. Department of Energy, Washington, DC, March 2015.

the past, this has not been considered a viable alternative, but recent decisions by the Administration[24] demonstrate that this approach is being investigated. This is also aligned with the recommendations from the Blue Ribbon Commission Disposal Subcommittee[25] that identified deep geological disposal as the most technically accepted method for safely isolating HLW from the environment.

DOE-Only Mined Salt Disposal

This disposal option is envisioned to be a deep, mined salt rock formation that would accommodate emplacement of DOE-generated waste only. The WIPP facility in New Mexico is an example of such a repository, although it is used for transuranic (TRU) waste only. Because calcine is HLW, as defined in the NWPA. its disposal at WIPP would require changes in both legislative and regulatory requirements documents, including the *WIPP Land Withdrawal Act*, as amended[26] and the *WIPP Hazardous Waste Facility Permit.*[27] Nevertheless, the WIPP facility provides an important basis for establishing assumptions related to the regulatory framework and waste form requirements that would be expected to be implemented for a DOE-only HLW salt repository. Acceptance of HLW is assumed to be likely because bedded salt formations are known to offer the following advantages for disposal of radioactive waste:

- Most deposits of salt are found in stable geological areas with very little earthquake activity; ensuring the stability of a waste repository.
- Salt deposits demonstrate the absence of flowing fresh water that could move waste to the surface. Water, if it had been or was present, would have dissolved the salt beds.
- Salt is relatively easy to mine.
- Rock salt heals its own fractures because of its plastic quality. That is, salt formations will slowly and progressively move in to fill mined areas and safely seal radioactive waste from the environment.

While waste form requirements specific to TRU waste disposed in the WIPP facility have been established, two key aspects that are currently practiced were assumed to also apply to an HLW salt repository. First, the AoA team assumed that, hazardous waste regulations would be applied in a limited manner to HLW disposed in a salt repository, similar to the manner that they have been implemented for WIPP. Second, the AoA team assumed that waste form requirements would be minimal (e.g., no free liquids), with no stringent protocol for leach testing, as was established for the Yucca Mountain facility. Accordingly, this disposal option was assumed to be more flexible than either the common or DOE-only hard rock mined repositories. A major factor in this assumption is that characteristics of the salt formations, as described above, allow less reliance on engineered barriers to isolate the waste from the environment. The AoA team also assumed that the salt environment may be more amenable to a variety of waste package configurations, although there may be limitations for some packages, such as the large

[24] *Presidential Memorandum, Subject: Disposal of Defense High-Level Radioactive Waste in a Separate Repository*, Memorandum for the Secretary of Energy, March 24, 2015.
[25] *Disposal Subcommittee Report to the Full Commission – Updated Report*, Blue Ribbon Commission on America's Nuclear Future, Washington, DC, January 2012.
[26] *Waste Isolation Pilot Plant Land Withdrawal Act*, Public Law 102-579, 106 Stat. 4777, 1992 (as amended by Public Law 104-201, 1996). Note that the legal definition of TRU waste is established in this Act.
[27] *Waste Isolation Pilot Plant Hazardous Waste Facility Permit*, NM4890139088-TSDF, New Mexico Environment Department, Santa Fe, NM, August 2015 (current revision).

(66-inch diameter) canister proposed for direct disposal of calcine.[28] This would require further investigation.

DOE-Only Deep Borehole Disposal

Deep borehole (DBH) disposal is another form of deep geologic disposal. The concept consists of drilling a borehole (or array of boreholes) into crystalline basement rock to a depth of about 5,000 m, emplacing waste canisters containing HLW in the lower 2,000 m of the borehole, and sealing the upper 3,000 m of the borehole. Waste in the DBH disposal system would be several times deeper than typical mined repositories, resulting in greater natural isolation from the surface and near-surface environment. The disposal zone in a single borehole could contain about 400 waste canisters of approximately 5 m length. The borehole seal system would consist of alternating layers of compacted bentonite clay and concrete. Asphalt may also be used in the shallow portion of the borehole seal system. For this AoA, only DOE waste is assumed to be included.

Although relatively simple in concept, actual implementation of DBH disposal requires assessment of many specific elements of the disposal system and has yet to be attempted. Nevertheless, low permeability and high salinity in the deep continental crystalline basement at many locations suggest extremely limited interaction with shallow fresh groundwater resources,[29] which is the most likely pathway for human exposure. These and other conditions led to the assumption that disposal in a DOE-only deep borehole will have limited waste form performance criteria, similar to WIPP, due to the favorable geometry, thermodynamics, and geochemistry, at the planned disposal depths, which eliminate contaminant transport pathways back to the biosphere.

The limitations on the canister configuration may lead to relatively high costs per volume of waste disposed and limit the applicability of this disposal concept to small quantities of problematic waste streams. For example, disposal of the 4,400 m^3 of calcine in DBHs is estimated to require approximately 80 boreholes, and require over 20 years, assuming that two drill rigs would be operating simultaneously. A detailed discussion of the DBH option, its maturity, and estimated number of boreholes is available in *Volume 2 – Detailed Report*.

In-Place Entombment/Disposal

Although discussed as part of the disposal options, this scenario is actually a combined processing/disposal strategy. In this alternative, the calcine would not be retrieved, but rather remain in place. The approach, as envisioned, involves filling the void volume around the binsets within the vaults, as well as any void volume within the bins, with grout. This would have to be accomplished in a systematic manner to maintain structural integrity throughout the entire grout placement and stabilization process. Feed and instrumentation piping into the vaults and bins would be cut, volume reduced (i.e., smashed/flattened) and abandoned in place in the vault prior to its being filled with grout. Any remaining pipe sections would also be filled with grout. Access risers would be sealed for permanent closure. Various grout formulations may be required for the different applications necessary to minimize remaining voids (i.e., to some determined maximum allowable percentage) in the final structure. The resulting monolith would require long-term institutional monitoring. This option presents the least costly processing/disposition strategy, by far, of all other alternatives, which is the primary reason it was considered. However, it also represents the most radical departure from existing regulations and

[28] Hill, T.J., et al., *Canister Design for Direct Disposal of HLW Calcine Disposal Produced at the Idaho National Engineering and Environmental Laboratory*, WM-4521, presented at Waste Management Symposium 2004, February 29 – March 4, 2004, Tucson, AZ.

[29] Park, Y.-J., E.A. Sudicky, and J.F. Sykes, "Effects of shield brine on the safe disposal of waste in deep geologic environments," *Advances in Water Resources* **32**: 1352-1358, 2009.

requirements related to disposal of HLW, which currently mandate deep geologic disposal. Additionally, this approach would not produce a final waste form that is in compliance with the current EPA regulations related to disposal of hazardous materials. Accordingly, this option represents the most challenging to obtain regulatory or stakeholder acceptance, and is likely not feasible.

4. PRE-SCREENING PROCESS AND RESULTS

Pre-screening was conducted using summary-level, equally-weighted, qualitative criteria to provide relative scoring (i.e., positive, negative, or neutral) of the identified processing category options. For the pre-screening step, only the general categories of technologies were considered (e.g., Vitrification, Low Temperature Stabilization, etc.) rather than all of the variants included within those categories. The pre-screening results are presented in Table 1.

Table 1. Summary results of pre-screening step.

Alternative	Cost	Schedule	Implementability	Acceptability	Result
Package for Direct Disposal	+	+	0	—	✓
Package for Offsite Treatment	0	0	0	—	✓
Vitrification	0	0	—	+	✓
HIPing	0	0	—	0	✓
Low Temp Stabilization	+	0	0	—	✓
Steam Reforming	—	—	—	0	✕
Dissolution/Separations	–	—	—	—	✕
In Situ Entombment	+	+	+	—	✓

The processing options were evaluated using a common set of assumptions, which are included as an attachment to this summary report. For each criterion, a specific process option was considered to represent the best case scenario, and other options were then compared to this baseline. For example, the "implementability" criterion was assessed within the context of reuse of the IWTU facility, and the related constraints. Because the In Situ Entombment would not require re-use of IWTU at all, and thus eliminate the need for its near term decontamination, it received a "positive" rating. On the other hand, while "Package for Direct Disposal" is a relatively simple flowsheet, and is assumed to be readily implemented into the IWTU facility with minimum modifications and no added footprint, it would require decontamination of the facility (e.g., FBSR vessels and piping) prior to re-use of IWTU. Accordingly, this option received a "neutral" rating. Finally, the complexity of high-temperature processes (e.g., HIPing, vitrification) would mandate a significant increase in the IWTU footprint due to the need for off-gas treatment systems in addition to the primary processing technology. As a result, these would require an annex or other separate facility, and received a "negative" rating.

The primary metric for down-selection during pre-screening was to eliminate all alternatives that received at least two negative ("—") assessments. This was considered to be appropriate because each summary-level criterion used during pre-screening actually represents multiple criteria and characteristics that, when combined, are assumed to be nominally equally weighted. As indicated in the table, only two of the processing category options were eliminated during the pre-screening, leaving six of the initial eight for further, more detailed screening and analysis.

5. DETAILED SCREENING AND ANALYSIS RESULTS

Based on the results of the pre-screening, 37 combined alternative scenarios remained for detailed screening (see Table 2). These scenarios provided four different disposal options for each of nine processing options, as previously described, resulting in 36 scenarios. Additionally, the in situ entombment was included as a standalone option for consideration.

Table 2. Combined alternative scenarios considered during detailed screening and analysis.

Combined Alternative Scenarios					
Processing Options	**Disposal Options**				
	In-place	Common Mined Hard Rock Repository	DOE-only Mined Hard Rock Repository	DOE-only Mined Salt Repository	DOE-only Deep Borehole
In Situ Entombment	✓				
Direct Vitrification Using JHCM in BSG		✓	✓	✓	✓
Direct Vitrification Using CCIM in Tailored Glass		✓	✓	✓	✓
Direct Vitrification Using CCIM in Glass-Ceramic		✓	✓	✓	✓
Direct HIPing with No Additives		✓	✓	✓	✓
HIPing in Glass-Ceramic		✓	✓	✓	✓
Low-Temperature Stabilization in Grout		✓	✓	✓	✓
Low-Temperature Stabilization in CBPC		✓	✓	✓	✓
Package for Offsite Treatment		✓	✓	✓	✓
Package for Direct Disposal		✓	✓	✓	✓

Note that two alternatives that passed the preliminary screening were further evaluated and screened out prior to detailed analysis. Long-term Storage (i.e., prior to any retrieval or processing actions) was initially considered a variant for all processing option. However, within the time frame considered (i.e., 100 years) this variant did not appear to provide any overall benefit, and would likely not be acceptable to stakeholders. Concerns were also identified related to potential impacts to retrieval due to agglomeration over time into very hard layers. Thus, it was eliminated from further consideration. In addition, the In Situ Entombment option was eliminated. This was primarily driven by a consensus among the AoA team members that, while this likely offered the fastest and least costly option, the final condition did not represent an environmentally responsible solution, and would not be acceptable to stakeholders.

5.1 Evaluation Criteria Descriptions

The 37 scenarios were first screened and the remaining options further evaluated using the weighted criteria developed by the AoA, as summarized in Table 3 and documented in the Review Plan. The criteria include safety, regulatory compliance, technical feasibility, operability and maintainability, cost and schedule, and stakeholder acceptance factors. The criteria were developed to help demonstrate how a

Table 3. Processing and disposal criteria descriptions and goals.

Processing and Disposal[a,b] Criteria Descriptions	
Criteria	**Goals**
Safety Weight: 10%	• Ensure the processing option, including both retrieval and treatment steps, minimizes hazards needing controls (especially active controls). • Ensure the processing option minimizes facility Hazard Category and Safety Class structures, systems, and components (i.e., allows facility segmentation, Safety Significant SSCs); and readily facilitates implementation of DOE-STD-1189-2005.
Weight: 10%	• Ensure the disposition option, including packaging and transportation steps, minimizes hazards needing controls (especially active controls).
Regulatory compliance Weight: 10%	• Provide high confidence of meeting Federal related regulations and/or expectations, or of obtaining acceptance for the option, such as "Road Ready by 2035" (i.e., from the Idaho Settlement Agreement), or BDAT equivalency to HLVIT. • Provide high confidence of meeting state related regulations and/or expectations, or of obtaining acceptance, such as the Site Treatment Plan (i.e., resulting from the FFCA), the RCRA Part B Permit, and the NEPA Record of Decision.
Weight: 10%	• Provide high confidence of achieving regulatory acceptance for the waste form, including but not limited to, RCRA characteristic waste and listed waste standards, the waste acceptance criteria for the disposal facility, and waste form qualification protocol for a non-borosilicate glass composition.
Technical feasibility Weight: 25%	• Mature technology with limited difficulty to further mature. (*Note: This addresses the confidence that the technology can be matured, as opposed to the cost of maturing it, or the complexity of the system and related operability/ maintainability impacts, which are considered in these other criteria.)* • Consistently meet requirements for downstream processing to ensure consistent in-process streams and products. • Applicable to treatment of SBW product, if required.
Weight: 35%	• Consistently meet waste form performance requirements for disposal.
Operability and maintainability Weight: 20%	• Minimize process/operating and maintenance complexity. • Ease of start-up and shut-down. • Minimize volume and complexity of disposition of secondary waste streams. • Maximize probability of consistently meeting target production rates.
Cost and schedule Weight: 25%	• Minimize total project cost. • Minimize near term cost and peak year cost. • Optimize use of existing facilities / process capabilities/utilities with minimum modifications. • Maximize throughput rate/minimize lifecycle processing schedule.
Weight: 35%	• Provides efficient final waste form volume for disposal option. • Disposal package configured to optimize disposal volume.
Stakeholder acceptance Weight: 10%	• Achieve acceptance from local/regional stakeholders (e.g., Citizen's Advisory Board, Snake River Alliance, other stakeholder groups and Tribal Nations), considering the following factors: ✓ Use of thermal versus non-thermal technologies ✓ Offsite versus onsite processing • Achieve acceptance from external stakeholders (i.e., DNFSB, NRC, EPA, external processing states if applicable), considering the following factors: ✓ Waste form acceptance confidence ✓ Process safety
Weight: 10%	• Achieve acceptance from external stakeholders (i.e., disposal state, corridor states, disposal facility), considering the following factors: ✓ Waste form acceptance confidence ✓ Transportation strategy

a. Disposal criteria are shown in the shaded rows.
b. Separate Processing and Disposal scores constitute 75% and 25%, respectively, of the combined total score for each alternative.

Table 4. Example of processing and disposal goals, measures, and definitions for the Safety Criterion.

Processing and Disposal[a,b] Criteria Descriptions		
Criteria	**Goals**	
Safety – Processing	• Ensure the processing option, including both retrieval and treatment steps, minimizes hazards needing controls (especially active controls). • Ensure the processing option minimizes facility hazard category and safety class structures, systems, and components (SSCs) (i.e., allows facility segmentation, Safety Significant SSCs); and readily facilitates implementation of DOE-STD-1189-2008.	
Safety – Disposal	• Ensure the disposal option, including packaging and transportation steps, minimizes hazards needing controls (especially active controls).	
Criteria	**Measure**	**Definition**
Safety – Processing **Total Criterion Weight: 10%**	The processing option, including both retrieval and treatment steps, minimizes hazards needing controls (especially active controls). Measure Weight: 50%	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.
	The processing option minimizes facility Hazard Category and Safety Class SSCs (i.e., allows facility segmentation, Safety Significant SSCs); and readily facilitates implementation of DOE-STD-1189-2008. Measure Weight: 50%	5 = Facility Hazard Category is lowest possible, MAR is minimized, provides minimum Safety Class SSCs, interfaces are well understood, hazards are easily identified and mitigated. 3 = Incremental increase in hazard/safety related criteria (i.e., MAR, Safety Class SSCs, complex interfaces, new/less-defined hazards, etc.) 1 = A significant increase in safety-related risks and overall level of mitigation required, as compared to other alternatives.
Criteria	**Measure**	**Definition**
Safety – Disposal **Total Criterion Weight: 10%**	The disposal option, including both packaging and transportation steps, minimizes hazards needing controls (especially active controls). Measure Weight: 100%	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.

a. Disposal criteria are shown in the shaded rows.
b. Separate Processing and Disposal scores constitute 75% and 25%, respectively, of the combined total score for each alternative.

particular option meets the goals of the CDP mission. Steps were taken to minimize duplication effects on scores. Where appropriate, each criteria includes goals related to both processing and disposal options. Specific, quantitative (to the extent practicable) measures, weights, and definitions were also identified for each criterion. Table 4 provides an example of the safety criteria goals, definitions, measures, and weights. The full set is documented in the Review Plan.

5.2 Processing and Disposal Option Assumptions

The previous discussions of the various processing and disposal options that were considered mentioned some of the key assumptions related to those alternatives. These are part of a comprehensive set of assumptions that was established to provide the framework for scoring the identified processing and disposal options. Assumptions were developed for each of the specific evaluation criteria, as well as general assumptions that were applicable to the overall system and related processes (see Appendix A).

5.3 Detailed Screening Results

Once each of the 37 scenarios had been scored, the second screening was performed. Scenarios with very low scores were immediately screened out. For example, offsite processing options were eliminated because they represent increased safety risks without any significant cost benefit. Specifically, the existing facilities that could process calcine would require significant modification to accommodate the dry, granular material. Additionally, this option requires multiple packaging, handling, and transportation steps, which often represent the greatest risks to DOE-EM projects. The direct HIPing with no additives option was also eliminated from further consideration due to its relatively high cost to produce a waste form that may be difficult to qualify for some of the disposal options (e.g., hard rock mined repositories), while providing no added benefit from the additional cost for the disposal options that are assumed to accept less robust waste forms (e.g., mined salt or DBH disposal).

The next consideration for reducing the number of options for more detailed analyses was related to the GAO Best Practices that recommend a baseline alternative be identified for comparative analysis. For the CDP, this is the option of HIPing in glass-ceramic. Additional eliminations were influenced by the uncertainty in the disposal path, and related requirements (i.e., Waste Acceptance Criteria). Specifically, the AoA team decided to select the variant within each processing category that, based on the assumptions and resulting scores, would provide the best overall performance for processing the calcine inventory. For the vitrification option, this resulted in selection of the CCIM due to its greater flexibility in waste form chemistry, operational temperatures, and potentially improved waste loadings. For the low-temperature stabilization option, the CBPC variant was selected due to its potential for much higher waste loadings, as compared to a saltstone-like grout waste form, and thus lower final waste form volume. Additionally, the final waste form is more robust, in general. The combined results of the two screening steps are depicted in Figure 2.

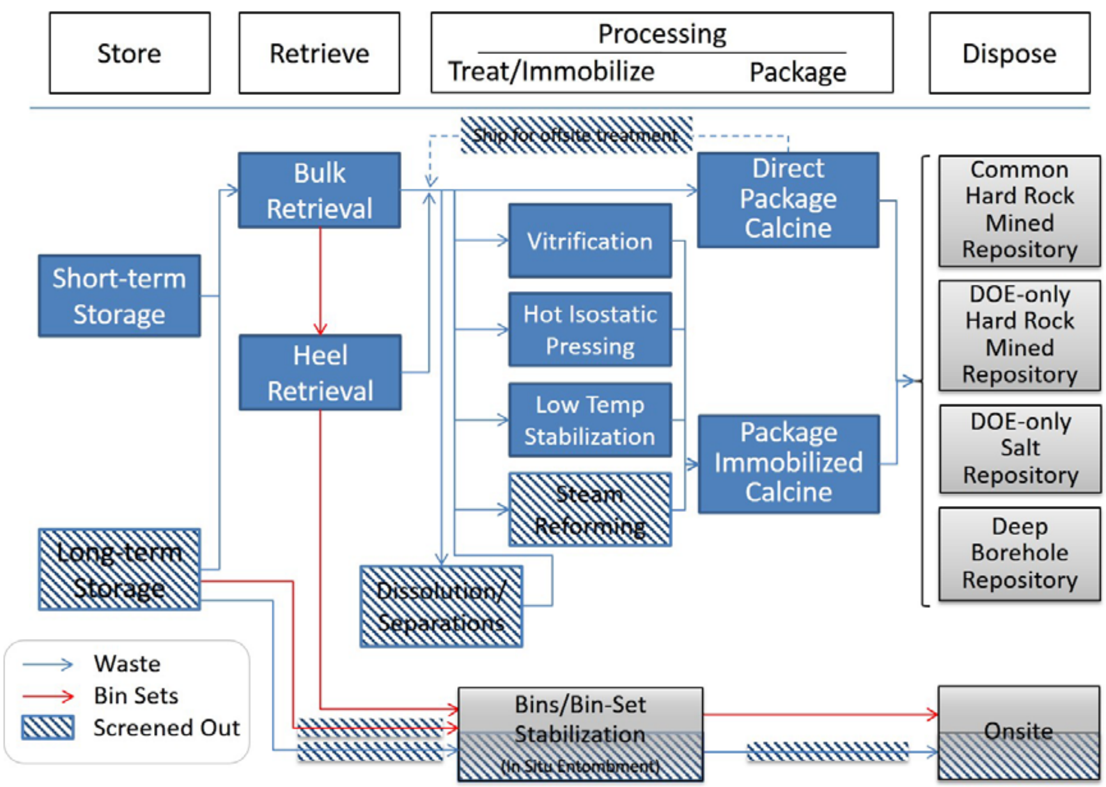

Figure 2. Remaining options after pre-screening and initial detailed screening.

5.4 Detailed Analysis Results

Four processing alternatives remained for the final detailed analysis, including package for direct disposal, vitrification with CCIM in tailored glass, HIPing in a glass-ceramic, and low-temperature stabilization in CBPC. The raw scores, assumptions, and resulting composite scores that led to selection of these options are available in *Volume 2 – Detailed Report*.

Error! Reference source not found. summarizes the results of the initial detailed analysis of the combined scenarios of the four processing and four disposal options, or 16 scenarios. Using the baseline weighted criteria, the package for direct disposal option scored the highest of all disposal options. In contrast, the current baseline, HIPing in glass-ceramic, scored the lowest of all disposal options. While HIPing produces a robust waste form, it is significantly different in composition from the accepted BSG waste form. Thus, not only will the waste form itself have to be approved for HLW disposal, qualification testing protocol will also have to be developed, validated, and accepted. As a result, the HIPing option scored lower than CCIM because this technology will produce waste forms that are more similar to the baseline BSG (i.e., crystalline tolerant BSGs and IPGs), and thus assumed to be more readily qualified. The Direct Disposal option, while not producing a robust waste form, is so much less costly than the other options that the risk (and cost) associated with approving the Direct Disposal waste form are readily offset, while presenting virtually no risk related to technical maturity.

Table 5. Score and relative rank for each processing/disposal pair.

Processing Option	Disposal Option	Score	Relative Rank By Disposal Option
Package for Direct Disposal	Common Mined Hard Rock	75	1
	DOE Mined Hard Rock	78	1
	DOE Mined Salt	85	1
	DOE Borehole	80	1
Direct Vit using CCIM in Tailored Glass	Common Mined Hard Rock	57	2
	DOE Mined Hard Rock	59	2
	DOE Mined Salt	65	2
	DOE Borehole	61	2
Low Temp Stabilization in CBPC	Common Mined Hard Rock	54	3
	DOE Mined Hard Rock	56	3
	DOE Mined Salt	64	3
	DOE Borehole	60	3
HIPing in Glass Ceramic	Common Mined Hard Rock	53	4
	DOE Mined Hard Rock	55	4
	DOE Mined Salt	61	4
	DOE Borehole	57	4

Note that in the last column, it is coincidental that, when using the baseline criteria weightings, the relative rank for each processing/disposal pair is the same. This is illustrated in the sensitivity analysis presented below (refer to Table 6). However, it should also be noted that some of the scores are very close (i.e., <2% difference), and when the uncertainties related to the assumptions are considered, these scores and resulting rankings should be considered equal. For example, the CBPC option is ranked above HIP for disposal options that are assumed to require a robust waste form, although the scores are virtually the same (i.e., 54 versus 53 for Common Mined Hard Rock disposal, and 56 versus 55 for DOE-only Mined Hard Rock disposal).

These results were then scrutinized to demonstrate that the process implemented is as objective as possible and technically credible. Again, in consideration of the GAO recommended Best Practices, sensitivity analyses were performed on the results.[30] Specifically, the weights assigned to the measures for each criterion were systematically modified. For the sensitivity analysis performed for this AoA, seven alternative weighting scenarios were considered:

- Equal weighting across the six criteria
- Replicating for each of the six criteria, increasing one of the criterion weights to 50% and allocating the remaining 50% equally across the remaining five criteria

This process provides insight to how sensitive the results are to the assumptions because these are intrinsic to the review criteria and measures established. In fact, most of the assumptions are organized into categories similar to the criteria (i.e., cost, operability, regulatory, technical, safety, and general). Thus, significantly increasing the weight of a specific criteria (i.e., from 10% to 50%) effectively increases the influence of the assumptions tied to that criteria, both positively and negatively. abling fully informed decisions.

Table 6 summarizes the results of the sensitivity analysis.

Package for direct disposal is the highest ranked processing option for every disposal option in all but two of the alternative weighting scenarios. The exceptions involved the scenarios in which 1) the regulatory weight was increased to 50% and 2) the stakeholder acceptance weight was increased to 50%. This is because the weights applied to those criteria were selected to ensure that an alternative was not eliminated solely for regulatory or stakeholder acceptance reasons, as requested by EM senior management. In general, when disposal requirements drive more-stringent waste form performance characteristics, the CCIM vitrification technology is preferred over other options. The sensitivity analysis provides insight into the overall AoA approach to enabling fully informed decisions.

[30] Note that the approach of separating the process options from the disposal options and evaluating each pair separately provides a comprehensive sensitivity analysis of the impact of the key assumption related to the disposal path.

Table 6. Sensitivity analysis results from varying criteria weightings.

		Relative Rank By Disposal Option							
Processing Option	Disposal Option	Baseline	Equal Weights	Safety 50%	Regulatory 50%	Technical 50%	Operability 50%	Cost / Schedule 50%	Stakeholder 50%
Package for Direct Disposal	Common Mined Hard Rock	1	1	1	3	1	1	1	3
	DOE Mined Hard Rock	1	1	1	2	1	1	1	3
	DOE Mined Salt	1	1	1	1	1	1	1	1
	DOE Borehole	1	1	1	1	1	1	1	2
Direct Vit using CCIM in Tailored Glass	Common Mined Hard Rock	2	2	3	2	2	2	3	1
	DOE Mined Hard Rock	2	2	3	3	2	2	3	1
	DOE Mined Salt	2	2	3	3	2	2	3	2
	DOE Borehole	2	2	3	3	2	2	3	1
Low Temp Stabilization in CBPC	Common Mined Hard Rock	3	4	2	4	3	4	2	4
	DOE Mined Hard Rock	3	4	2	4	3	4	2	4
	DOE Mined Salt	3	4	2	4	3	4	2	4
	DOE Borehole	3	4	2	4	3	4	2	4
HIPing in Glass Ceramic	Common Mined Hard Rock	4	3	4	1	4	3	4	2
	DOE Mined Hard Rock	4	3	4	1	4	3	4	2
	DOE Mined Salt	4	3	4	2	4	3	4	3
	DOE Borehole	4	3	4	2	4	3	4	3

While there is consistency at the top of the rankings under the alternative weighting scenarios, there is some re-ordering among the other options, which is to be expected. Overall, however, the results of this sensitivity analysis demonstrate that the AoA process developed and implemented for calcine disposition is objective and technically sound.

As part of the detailed analysis step, a cursory technology readiness assessment (TRA) was conducted for the four processing options considered. These results are shown in Table 7. Due to its simplicity, the package for direct disposal option is the most mature (i.e., virtually no new technologies must be developed except for retrieval). The CCIM technology was determined to be the second most mature, which is also consistent with the sensitivity analyses. The process flowsheets that formed the basis of this TRA, as well as the cost estimates, are provided in Appendix B. Details of the TRA are provided in *Volume 2 – Detailed Report.*

Table 7. Technology Readiness Levels of processing alternatives.

Critical Technology Element	Direct Disposal	CBPC	CCIM	HIP
Retrieval and pneumatic transfer	3	3	3	3
Batching, sampling, and mixing (dry)	7	2	5	4
Waste form development	N/A	2	3	3
Can/container	7	2	5	4
HIP/melter/mixer (wet mixing)	N/A	4	6	4
Filling and closure	7	2	7	4
Bake-out and/or process off-gas	7	5	5	4
Canister loading and closure	N/A	N/A	N/A	4
Remote operation and maintenance	6	2	6	4

The final step in the detailed analysis included development of general cost estimates for implementation of each of the four processing options. General processing assumptions were established to facilitate development of the cost estimates, as follows:

1. A standard canister of nominal 2-feet diameter by 10-feet long will be used for all processing options. It is recognized that this canister geometry is not feasible and/or optimum for some disposal scenarios (e.g., DBH). It is used solely for cost comparison purposes for this AoA.
2. Canisters are assumed to be 90% full.
3. Retrieval requirements and associated cost are the same for all options.
4. For the options that require an annex to the existing IWTU facility, it was assumed to be nominally the same size and cost.
5. A disposal path is assumed to be available at the time that processing operations are initiated such that only storage for packaging and transportation storage are required, as the baseline[31].

Several key assumptions were made regarding waste loading, throughput rate, operating space requirements, etc, for each option considered. These are summarized in Table 8. The resulting comparative cost estimates are provided in Table 9. As previously discussed, these cost estimates do not include disposal costs, and as such are not full LCC estimates. While these are rough order of magnitude (i.e., Class 5, -50%/+100%) estimates, with the point estimate reported in Table 9, general trends can be observed. For example, the more complexity and hazards within the processing technology, the higher the total estimated cost, which is as expected. Additional details of development of these estimates, including all related assumptions, are provided in *Volume 2 – Detailed Report*.

Table 8. Key process-specific assumptions for developing cost estimates.

	Direct Disposal	**CBPC**	**CCIM**	**HIP**
Processing Units	1	1	2	3
Waste loading (wt%)	100%	40%	55%	55%
Total Additive (m^3)	0	6600	3600	3600
Pre Treated Waste Volume (m^3)	4400	11000	8000	8000
Gross Volume Reduction (%)	0	20	25	35
Post Treatment Volume	4400	8800	6000	5200
Number of Canisters	5,500	11,000	7,500	6,500
Total Waste Volume (m^3)	4,900	9,800	6,700	5,800
Annex required	no	yes	yes	yes
Years of operation required	8	8	8	12

Table 9. Cost estimates for processing options.

	Direct Disposal	**CBPC**	**CCIM**	**HIP**

[31] Long term storage costs are considered as a separate item in the detailed cost estimate and are based on the resulting total processed waste form volumes for each option. These costs are available in the *Volume 2: Detailed Report*.

Project Management	34.1	56.7	110.1	78.6
Design	17.6	36.9	92.6	57.3
Start-Up/Commissioning	5.0	10.9	21.1	15.1
Construction	228.0	535.5	1000	744.3
Primary Process Equipment	0.0	16.2	216.9	98.2
Operations	254.4	556.9	573.5	972.7
Storage	67.0	122.0	87.0	77.0
TOTAL ($M)	**606.1**	**1,335**	**2,101**	**2,043**

The estimated costs in Table 9 are based on the assumption that long term storage is not required (i.e,, only limited storing/staging for shipment is required) for the waste packages produced. If a disposal option is not available, long term storage will add an estimated $370.3M, $765.5M, $517.8M, and $447.4M to the Direct Disposal, CBPC, CCIM, and HIP options, respectively. As with the processing option cost estimates, these are the point estimates for Class 5 (+100%/-50%) cost estimate ranges.

6. OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

An AoA was conducted for the CDP during April to December 2015. Based on the data reviewed and developed during that effort, key observations, conclusions, and recommendations were identified for consideration.

Observations

1. The selection of HIPing as the baseline technology was heavily influenced by the final waste form volume and assumed per-canister cost for disposal in Yucca Mountain of $620,000. Due to the current uncertainty of the disposal path, this presumption is no longer valid.

2. Significant advances have occurred in development of advanced waste forms and processing technologies since the previous alternatives analyses and ultimate selection of HIPing in 2009. Specifically, the CCIM technology, especially when coupled with tailored waste form chemistries (e.g., IPG, crystal-tolerant glass, glass-ceramics), performs much better at higher waste loadings than suggested by the assumptions used during those previous alternatives analyses.

3. The possibility of a DOE-only disposal facility, regardless of the configuration or geology, provides disposal options and related regulatory frameworks that may accommodate a broader range of acceptable waste forms due to either more favorable geologies (i.e., salt formations and DBH), or opportunities to restructure the regulatory framework (i.e., less influence from the Yucca Mountain model for a combined repository). Such options were not available during previous alternatives analysis and selection processes.

4. Retrieval is required for all feasible options considered and is not a discriminator for this AoA. Retrieval of calcine represents a significant technical and engineering challenge.

5. There are regulatory and stakeholder risks associated with the Package for Direct Disposal, which are highly dependent on the disposal option that is realized.

Conclusions

1. Selection of the most appropriate processing technology is highly dependent on the disposal path, and the associated waste form performance requirements. A fully informed final decision regarding processing of the calcine cannot be made until the disposal path is known along with the associated regulatory framework.

2. In general, salt bed formation disposal of DOE-only HLW appears to provide the most flexible and cost-effective disposal path, regardless of processing technology.

3. Package for direct disposal offers the best alternative for all disposal scenarios, when the baseline criteria weightings are used. However, if regulatory or stakeholder concerns have a greater influence, the process options that produce more robust waste forms are preferred.

4. CCIM vitrification provides the best processing option if a robust waste form is preferred.

5. The current baseline of HIPing appears to represent the least preferable processing technology for all disposal options based on the assumptions and supporting criteria. HIPing represents the highest operational safety risk (e.g., high pressures and temperatures) of all the processing options.

6. DBH disposal is technically feasible, but represents much more uncertainty related to the regulatory framework and overall waste form requirements that will be established. Additionally, the DBH configuration does not appear to be cost effective for calcine disposal due to the volume of waste. Calculation estimate that approximately 80 boreholes would be required.

7. Package for Direct Disposal is the lowest cost and most technically mature option.

Recommendations

1. The Calcine Disposition Project should be divided into two subprojects: a) Calcine Retrieval, and b) Calcine Processing. The project near-term priorities should focus on calcine retrieval activities, and limited technology maturation to better inform future processing decisions.

2. A final decision regarding the processing technology should be deferred until the disposal path is better defined, as well as its expected regulatory framework, and resulting waste form performance requirements.

3. An independent AoA should be conducted for the retrieval system. It should consider impacts of the as-retrieved calcine feed to downstream unit process steps, and how to optimally manage and subsequently condition these materials such that an acceptable feed is provided (particle size, physical uniformity, blending/chemical uniformity, etc.).

4. Efforts should be accelerated on development and testing of the most effective retrieval technologies and systems. Significant progress can be made in advance of processing and disposal to address key retrieval risks and uncertainties.

5. The Calcine Retrieval Subproject should consider the concept of a full-scale radioactive demonstration of the retrieval and transport system, to include retrieval from CSSF #1 to CSSF #6. This would potentially allow for RCRA closure of CSSF #1, which is considered the most suspect CSSF from a structural integrity perspective due to its concentric tube bin configuration.

6. There may be specific portions of the calcine inventory that were generated from processing SBW only (i.e., no HLW feed) that could potentially be granted Waste Incidental to Reprocessing status, if it can be differentiated from other HLW calcine. If such differentiation is possible, this SBW calcine could potentially be retrieved and packaged for direct disposal along with the stem-reformed SBW product from IWTU. This should be investigated for feasibility.

7. Additional sampling of actual calcine should be considered, especially during retrieval demonstration efforts, to support development of processing options.

APPENDIX A

Idaho Calcine Disposition Project Analysis of Alternatives Supporting Assumptions

Idaho CDP Analysis of Alternatives - Supporting Assumptions

General Assumptions

1. All disposition options, with the exception of in-place disposal/entombment, will require retrieval of the calcined solids. Accordingly, this step in the overall processing and disposition strategy is not a discriminator. Nevertheless, this activity represents a significant technical challenge and will require a separate, focused Analysis of Alternatives to determine the most cost-effective and reliable solution(s).
2. In-place disposition, while technically feasible, is not a viable alternative due to the ramifications related to the Nuclear Waste Policy Act (i.e., definition of HLW and required disposal path), nor does it appear likely that this strategy could be demonstrated to offer a solution that is protective of the environment to an acceptable degree.
3. In-place disposal will never be accepted by stakeholders or regulators and is not a viable option.
4. Offsite treatment will be extremely challenging to gain acceptance by external regulators and stakeholders (i.e., in the processing state) without some significant state-specific benefit that could be used to leverage support. This challenge will be further exacerbated if this option does not provide a significant benefit over other options.
5. Interim decay storage (i.e., 100 years or less) of the calcine prior to retrieval and processing, while reducing the overall level of radioactivity, does not appear to provide any benefits related to reduction of MAR and/or hazard class of the facility, and will likely result in the same number of Safety Class systems for the future processing facility. Additionally, it may lead to increased difficulties in retrieval due to continued compaction and potential agglomeration of the calcined solids within the binsets.
6. Disposition alternatives that include interim decay storage will likely never be accepted by stakeholders or regulators since this strategy does not appear to offer any benefits (i.e., life cycle cost, schedule, risk reductions) and is thus, not a viable option.
7. Offsite processing options include only vitrification in a BSG matrix in existing facilities, either at DWPF or the planned WTP facility. New offsite facilities would not be constructed. Introduction of the calcine powder into the processing stream at either of these facilities will require significant modification to the feed preparation system within these plants since they are both designed to manage slurry feeds.
8. A disposal facility will be available before the untreated calcine is allowed to be shipped offsite to a treatment facility.
9. For purposes of the analysis, the "Disposal" criteria include the packaging and transportation steps since the disposal facility configuration (i.e., mined versus borehole) will determine the package configuration, and consequently the transportation requirements.
10. Due to the calcine chemistry (i.e., high sodium and aluminum), vitrification in a BSG using JHCMs will offer the lowest waste loading, and thus larger final volume, as opposed to FePO and Glass-ceramic waste forms, that are assumed to provide nominally twice the waste loading as BSG.
11. Low temperature stabilization in grout (i.e., generic Portland cement, fly ash composition) will nominally result in the greatest final waste form volume, increasing the volume by 3X to 4X.
12. Low temperature stabilization in MgPO4 ceramic will provide nominally the same waste loading and final waste volume as FePO glass.
13. Direct HIPing with no additives will offer a nominal volume reduction of 50%.
14. Processing criteria are more objective than the disposal criteria since no actual disposal facility WAC is available for planning purposes and the framework for acceptance at each type of facility had to be assumed. Thus, the processing criteria scores constitute 75% of the total score, while the disposal criteria scores account for the remaining 25%.

15. Separating the processing options from the disposal options and scoring each paired set as a separate scenario provides a comprehensive sensitivity analysis for each processing option relative to the most impactful assumption – the disposal path. This is in compliance with an identified GAO best practice.
16. The ability to re-use existing facilities (i.e., IWTU) will be limited (i.e., cost-prohibitive) for more complex processing technologies (i.e., high temperature and/or high pressure) that involve several steps, especially those that require complete decontamination, dismantlement, and removal of all existing processing equipment, while retaining the structure.

Safety Assumptions

1. High temperature and high pressure processes (e.g., HIPing) represent the greatest safety risk.
2. Low temperature stabilization processes (e.g., $MgPO_4$) represent the lowest safety risk.
3. Disposition strategies that require more frequent transportation or multiple transportation steps represent greater risk. This will be driven by final waste form volume and treatment location (i.e., offsite treatment).
4. Processes that produce more robust waste forms represent lower risk during transportation than those that produce less robust waste forms (e.g., direct HIP versus direct packaging).
5. Offsite processing options represent an increased safety risk because this disposition strategy will require two shipments: from Idaho to the treatment facility and from the treatment facility to the disposal facility.
6. Introduction of dispersible powders into the operating vitrification plants, which are designed to manage wet slurries only, will introduce new hazards that may significantly impact existing DSAs.
7. Achieving acceptable levels (i.e., ALARA principles) of contamination and radiation to allow personnel entry into the IWTU cells for installation of new equipment will likely be cost prohibitive and is not feasible.

Regulatory Assumptions

1. For a given disposal option, process options that are the same as or near to the accepted BDAT of HLVIT represent the lowest regulatory risk for acceptance. Thus, vitrification in a BSG will be lower risk than vitrification in an FePO glass, since it is a different glass composition, while FePO will be lower risk than grout.
2. Disposal in a co-mingled (i.e., DOE waste and commercial SNF) geologic repository will have the same regulatory framework as Yucca Mountain (i.e., WAPS, WASRD), which will carry the most stringent requirements for waste form characteristics and performance.
3. Disposal in a DOE-only hard rock mined geologic repository will have a regulatory framework that is influenced by the Yucca Mountain precedent, due to similarity, but will be more flexible than the specific requirements established for Yucca Mountain (i.e., WAPS, WASRD).
4. Disposal in a DOE-only mined salt repository will have a regulatory framework that is influenced by the WIPP precedent, due to similarity, and will have limited waste form performance requirements (e.g., no free liquids).
5. Disposal in a DOE-only deep borehole will have limited waste form performance criteria, similar to WIPP, due to the favorable geometry, thermodynamics, and geochemistry at the planned disposal depths that eliminate contaminant transport pathways back to the biosphere.

Technical Assumptions

1. For a given processing option, disposal paths that are expected to have less restrictive waste form requirements (e.g., co-mingled mined hard rock versus DOE only mined salt) will have an overall higher TRL, and will require less technology development//maturation since the operational envelope will be more flexible.

2. The SBW carbonate product will not be amenable to processing in high temperature processes without significant pre-conditioning due to redox control and/or gas generation concerns during processing.
3. For disposal options with less restrictive waste form requirements, off-spec products are assumed to be less likely, and thus ensuring compliant interfaces with downstream processes offer higher confidence.
4. All processing options considered were assumed to be readily matured and demonstrated to successfully meet the mission needs, based on available R&D and test data.

Operability Assumptions

1. Start-up/Shutdown of low temperature stabilization processes is assumed to require the greatest operator interface due to the need to flush the systems, recycle water, etc.
2. JHCMs are not amenable to thermal cycling due to refractory cracking concerns, while cold wall induction heating systems (e.g., CCIM, In-can melting) do not have this limitation. This makes start-up/shutdown for JHCMs more problematic, but procedures are well-established from West Valley and DWPF experiences.
3. For a given processing option, disposal options that have less restrictive waste form requirements, will offer a higher confidence in meeting target production rates. This is primarily driven by the limited ability to perform reliable in-process sampling and analysis of the calcine solids. This will result in a greater likelihood that the waste loadings will have to be reduced to ensure an acceptable final waste form.
4. Vitrification systems, regardless of the specific technology, are assumed to be more readily maintained than the HIP process due to operational experience within the DOE as well as internationally for these technologies. HIPing has never been deployed for remote, large-scale, radioactive ceramic production.
5. Waste loadings, and thus final waste volume, for offsite treatment options represent significant risk due to uncertainty as to how the calcine feed would be processed (i.e., blended with existing HLW, processed separately after water/chemicals added to make it compatible with the existing system, fed directly as powder after significant facility modification, etc.).

Cost Assumptions

1. All vitrification technologies will be nominally the same near term and peak cost, which are assumed to be similar to the HIP process.
2. Total Project Cost for processing accounts for nominal operational costs (i.e., system maintenance, materials, labor, energy, etc.).
3. Total Project Cost for disposal accounts for overall waste form volume produced and how efficiently its configuration (i.e., nominal packaging) uses the disposal volume. For example, due to low expected waste loading, the JHCM vitrification option in a BSG would result in the largest disposal volume, which would require more shipments, a larger disposal facility, etc. Thus, for a borehole disposal, this would be the least cost-effective due to the restrictive package geometry (i.e., proposed 0.17 m ID by 5 m long, ~0.1 m^3 volume). However, it would represent the most efficient use of the disposal volume.
4. In general, hard rock mined repositories offer the least flexibility in configuration design, and will generally result in lower waste emplacement efficiency, thus increasing the relative cost per unit volume disposed. Mined salt repositories and boreholes offer greater emplacement efficiencies. Thus, for two processing options in a given disposal scenario that score the same for all other criteria, the one that provides higher waste loading will generally be scored higher.
5. Offsite treatment options will provide near term/peak cost benefits since no new facilities will be required at the Idaho site; however, TPC will not benefit due to significant modifications required to radiologically contaminated facilities, as well as twice as many shipments.

APPENDIX B

Idaho Calcine Disposition Project Analysis of Alternatives Flow Diagrams for Processing Options

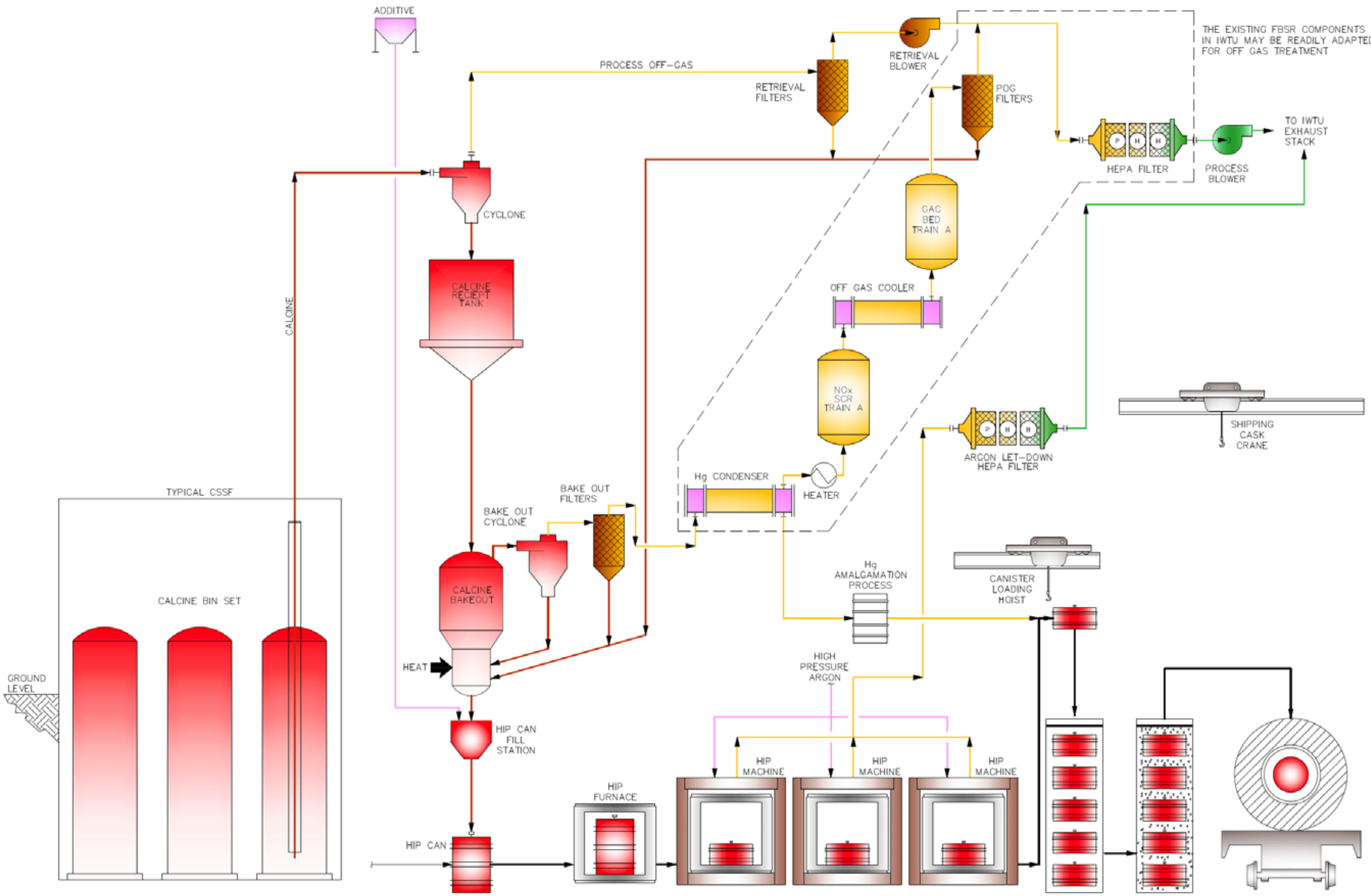

Figure B-1. Hot Isostatic Pressing in Glass-Ceramic Flow Diagram.

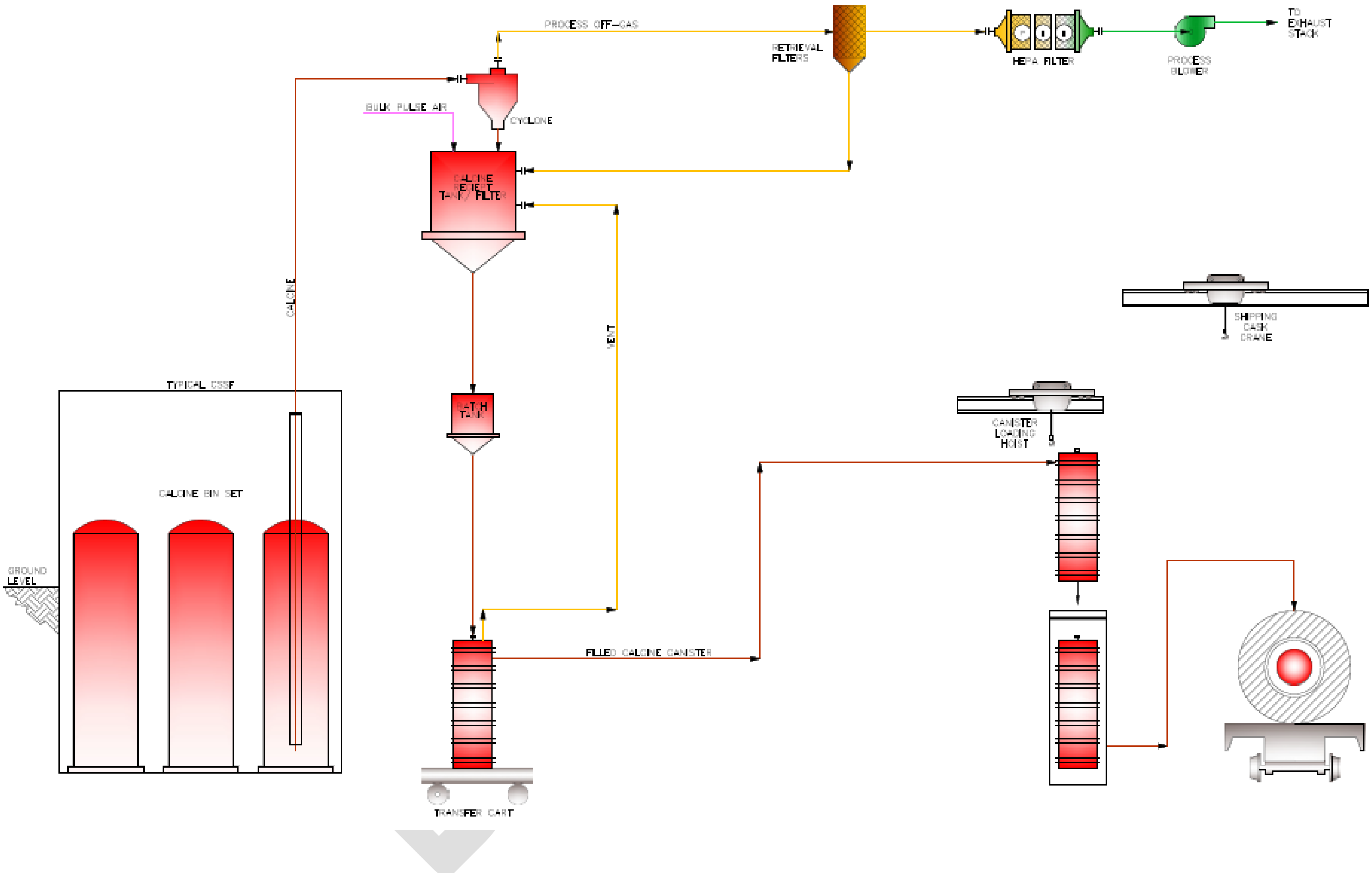

Figure B-2. Package for Direct Disposal Flow Diagram.

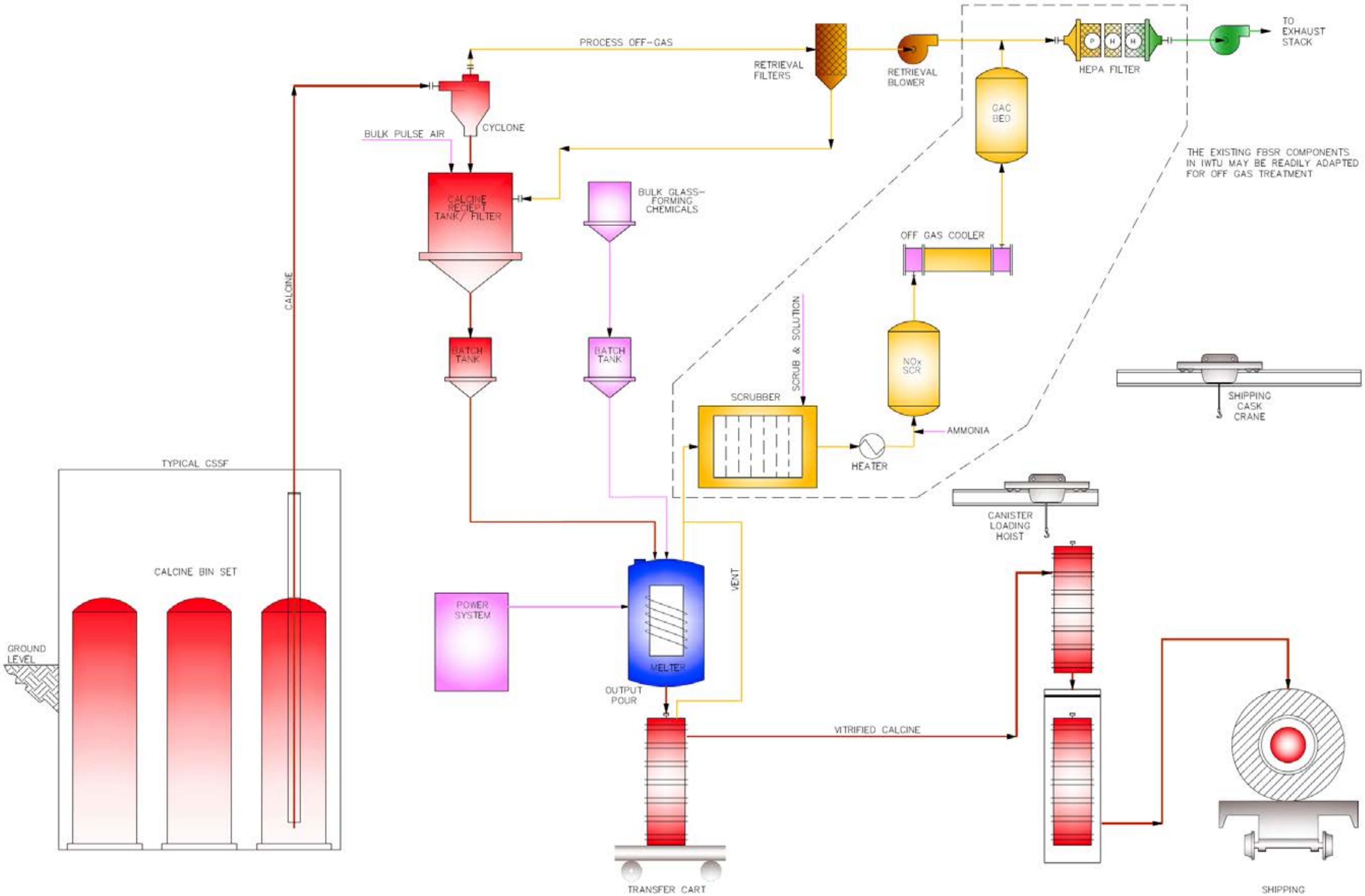

Figure B-3. Cold Crucible Induction Melting Flow Diagram.

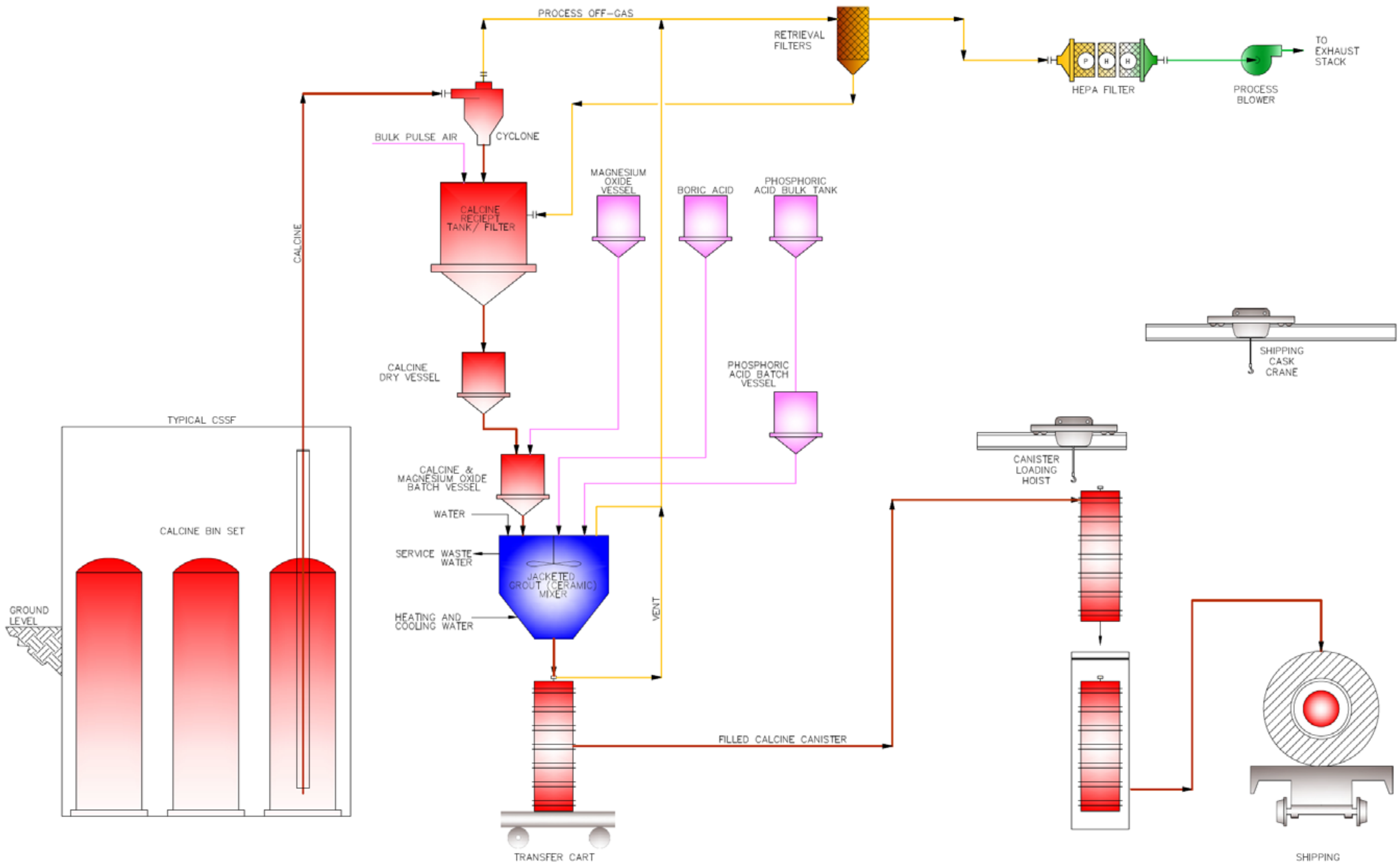

Figure B-4. Low Temperature Stabilization in CBPC Flow Diagram.