An Overview of Project Planning for Hot-Isostatic Pressure Treatment of High-Level Waste Calcine for the Idaho Cleanup Project - 12289

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ABSTRACT

The Calcine Disposition Project is responsible for retrieval, treatment by hot-isostatic pressure, packaging, and disposal of highly radioactive calcine stored at the Idaho Nuclear Technology and Engineering Center at the Idaho National Laboratory Site in southeast Idaho. In the 2009 *Amended Record of Decision: Idaho High-Level Waste and Facilities Disposition Final Environmental Impact Statement* the Department of Energy documented the selection of hot-isostatic pressure as the technology to treat the calcine. The Record of Decision specifies that the treatment results in a volume-reduced, monolithic waste form suitable for transport outside of Idaho by a target date of December 31, 2035. That target date is specified in the 1995 Idaho Settlement Agreement to treat and prepare the calcine for transport out of Idaho in exchange for allowing storage of Navy spent nuclear fuel at the INL Site. The project is completing the design of the calcine-treatment process and facility to comply with Record of Decision, Settlement Agreement, Idaho Department of Environmental Quality, and Department of Energy requirements. A systems engineering approach is being used to define the project mission and requirements, manage risks, and establish the safety basis for decision making in compliance with DOE O 413.3B, “Program and Project Management for the Acquisition of Capital Assets.” The approach draws heavily on “design-for-quality” tools to systematically add quality, predict design reliability, and manage variation in the earliest possible stages of design when it is most efficient. Use of these tools provides a standardized basis for interfacing systems to interact across system boundaries and promotes system integration on a facilitywide basis. A mass and energy model was developed to assist in the design of process equipment, determine material-flow parameters, and estimate process emissions. Data generated from failure modes and effects analysis and reliability, availability, maintainability, and inspectability analysis were incorporated into a time and motion model to validate and verify the capability to complete treatment of the calcine within the required schedule.

INTRODUCTION

The Calcine Disposition Project, a subproject of the Idaho Cleanup Project, has the responsibility to retrieve, treat by hot-isostatic pressure (HIP), package, and dispose of highly radioactive calcine stored at the Idaho Nuclear Technology and Engineering Center located at the Idaho National Laboratory (INL) Site in southeast Idaho. Calcine is a granular solid that is the product of thermally treating liquid high-level radioactive waste (HLW) produced during the reprocessing of spent nuclear fuel to recover uranium and liquid radioactive sodium-bearing waste from decontamination activities. The liquid radioactive waste was “calcined” at the Idaho Nuclear Technology and Engineering Center from 1963 until 2000 when the INL’s New Waste Calcining Facility was closed under the Resource Conservation and Recovery Act (RCRA)[1]. Currently, calcine is stored in six Calcine Solids Storage Facilities. Each calcine storage facility contains from three to 12 stainless steel tanks surrounded by a concrete vault. The calcine storage facilities are discussed in more detail below in the Calcined Solids Storage Facilities Overview section. The Department of Energy (DOE) selected HIP as the technology to treat calcine through a decision analysis process evaluating several treatment technologies. In the *Amended Record of Decision: Idaho High-Level Waste and Facilities Disposition Final*

Environmental Impact Statement [2, 3], DOE documented the selection of HIP as the technology to treat calcine to provide a volume-reduced, monolithic waste form suitable for transport outside of Idaho, with completion of treatment by a target date of December 31, 2035. That target date is specified in the 1995 Idaho Settlement Agreement [4] for completion of preparing the calcine for transport out of Idaho. The Amended Record of Decision also specified that the Integrated Waste Treatment Unit, which was built to treat the remaining radioactive sodium-bearing waste after the calciner was closed, be used after "suitable reconfiguration" for treating the calcine and other wastes while meeting associated safety and seismic design basis requirements [2, 3]. The design of the Integrated Waste Treatment Unit modified for the Calcine Disposition Project complies with the requirements of the Amended Record of Decision and other requirements documents including DOE orders and policies, federal regulations, the CH2M-WG Idaho, LLC, contract [5] with DOE to manage the Idaho Cleanup Project, state and local regulations, and industry standards.

In the sections below, the systems engineering approach that the Calcine Disposition Project used to comply with these requirements is discussed, including the systems engineering numbering (SEN) structure and the systems engineering approach to requirements management and risk management, along with the design-for-quality tools used in the systematic approach. Following this discussion, the treatment process and facility are described at a conceptual level.

PLANNING METHOD

Systems Engineering Approach

DOE O 413.3, "Program and Project Management for the Acquisition of Capital Assets" [6] defines systems engineering as:

> A proven, disciplined approach that supports management in clearly defining the mission or problem; managing system functions and requirements; identifying and managing risk; establishing bases for informed decision-making; and, verifying products and services meet customer needs.

Transformation of mission operational requirements into system architecture, performance parameters, and design details is the goal of systems engineering, according to the order.

Systems Engineering Numbering

To satisfy DOE's objectives, the Calcine Disposition Project has been organized into five functional areas: retrieval, treatment, packaging and handling, shipping, and plant facility and support. The overall function of each of these five areas is discussed below in the Calcined Solids Storage Facilities Overview section. Each of the functional areas was organized further into systems, and each system into subsystems. As the design progresses, the subsystems will be organized further into assemblies, and the assemblies will be organized by components so that each component of the overall process will have a unique identifying systems engineering number (SEN) with rollup to the functional area. These SENs are used in resource allocation for design and testing at the appropriate level for the design phase. For example, at the current conceptual design level, resources are allocated and charges are captured at the subsystem level. The same approach will be used through the later stages of design and into construction with charges captured at the assembly and component level. This approach for managing the systems allows design and construction management to allocate and redirect resources more efficiently by applying information from previous design stages to refine resource allocation planning.

Requirements Management

Requirements and risks were identified in a similar manner. Project-level requirements were identified from the upper-level governing documents and rolled down to the project technical and functional requirements. The upper-tier documents include the ICP contract [5, 7]; Amended ROD [2, 3]; DOE orders, policies, codes, and standards; federal regulations; Idaho Settlement Agreement [4]; Site Treatment Plan [8, 9]; Waste Acceptance System Requirements Document [10]; Transportation System Requirements Document [11]; Quality Assurance Requirements and Description [12] with its associated Quality Assurance Project Plan [13]; Waste Acceptance Product Specification [14]; and state and local regulations. In addition to the above requirements documents, system and subsystem requirements, as documented in the system and subsystem design descriptions, may include additional requirements from professional society codes and standards. Requirements for the project, regardless of the systems engineering level, are managed with the Dynamic Object-Oriented Requirements System (DOORS) software by International Business Machines (IBM) [15]. The database captures governing documents and the implementing documents for each requirement.

Risk Management

Project-level risks were documented in the project risk management plan. Technical risks that are more specific to the system and subsystem levels are captured in the system and subsystem design descriptions and in a technical risk management plan. Each risk identified carries an associated cost that is tracked at a project level. As the design progresses, the risks will be reevaluated, typically on a monthly basis for project-level risks, and added to, modified, or closed out, as appropriate.

Alternative Analysis

Through the course of the design process, the value engineering process for alternative analysis has been integral to planning and will continue to be used. This process ensures that DOE receives products that meet the department’s needs most efficiently and cost effectively. Also, the process ensures that decision making is being performed consistently according to common standards. Results of alternative analyses that are performed are reported at the appropriate level including in the system and subsystem design description documents.

Design-for-Quality Tools

The systematic design-for-quality approach practiced by the Calcine Disposition Project focuses on probabilistic analysis to design for quality and predictability to manage inherent variation at the earliest possible stages of design when it is most efficient and cost effective, rather than trying to fix problems subsequently at a higher cost [16]. Design based on probability is a volte-face approach to designing for a “factor of safety,” which may ignore randomness and variation—and miss the opportunity to manage and, thereby, minimize it [17].

Use of design-for-quality tools also provides a standardized basis for interfacing systems and subsystems to interact across system and subsystem boundaries and promotes system integration on a facilitywide basis to strengthen design attributes such as producibility in manufacturing and assembly, reliability, performance of technical requirements, and maintainability. Drawing heavily on tools such as Six Sigma [18], the Calcine Disposition Project design-for-quality approach incorporates quantitative assessment of design risk including interface analysis; failure modes and effects analysis; reliability, availability, maintainability, and inspectability (RAMI) analysis; and time and motion study, as discussed below.

Interface Analysis

A key aspect of designing-for-quality is interface management. Interfaces within functional area processes and facility and support systems and subsystems, and across processes and the facility and support systems and subsystems, must be managed to ensure that the overall process is efficient and cost effective in accomplishing the project mission. As a means to that end, the Calcine Disposition Project developed an interface matrix to identify these interfaces and the interface requirements (e.g., flow rates, materials of construction, or sizes).

Failure Modes and Effects Analysis

Failure modes and effects analysis (FMEA) is a procedure for analysis of potential failure modes within systems and subsystems for classification based on the severity and likelihood of the failure. The intent is to modify or eliminate features with a probability of failure—with a standardized quantitative assessment of design risk. The procedure assists a design team in identifying potential failure modes based on past experience and determining which of those failure modes have the highest risk, thereby enabling the team to design those failure modes out of the system. The procedure begins by identification of failure modes. Thereafter, the severity of the failure, probability of occurrence, and ease of detection are evaluated. Common guidelines were used during the project's FMEA evaluations to ensure consistency across systems and subsystems. Risk may be defined as the product of the severity, probability, and detectability. For the failure modes with the highest risk, mitigation plans were developed, and design data-need forms were completed. In most cases, additional testing was necessary for mitigation of the risk. Once the mitigation has been applied, the failure mode is reevaluated to determine whether the risk has been reduced to an acceptable level. It should be noted that some risks can never be mitigated because of outside interference or prohibitive cost. The procedure identifies these risks to management as those requiring monitoring to prevent the failures that cannot be mitigated. Through the FMEA procedure, the project identified several failure modes that require mitigation. Where applicable, further testing was identified to mitigate the failure. Failures that have the potential to result in health and safety consequences will be identified in a hazard and operability analysis. These failure modes will be further evaluated in accordance with DOE guidelines as being either safety class, safety significant, or non-safety and documented in the project's conceptual safety design report.

One failure mode of importance to the Calcine Disposition Project is the potential failure of a HIP machine. Because of high pressure and high temperature, the potential exists to release radionuclides if a failure occurs. Over the past 40 years, through the design improvement process, manufacturers of HIP machines have significantly reduced the potential for failures. A key industry initiative is the American Society for Mechanical Engineers (ASME) pressure-coded pre-stressed, wire-wound pressure vessels and yokes, which provide a "leak-before-break" design to mitigate this risk. Although the probability of a leak of argon gas, used in the machine to apply pressure isostatically, from the machine occurrence is low, the severity is sufficiently high to warrant a mitigation plan. During HIP treatment, the material at risk, the calcine, is contained in a vacuum-sealed can with the high pressure on the outside of the can. The can is contained within a HIP furnace within the ASME pressure-coded HIP vessel. The HIP machine is within a radiological-control cell with active ventilation. This defense-in-depth strategy employs multiple levels of containment to mitigate the potential failure modes and ensures the ultimate safety of workers.

A second important failure mode is the potential inability to produce an acceptable waste form. Calcine is a mixed HLW containing several characteristically hazardous metals. The current baseline for the project requires containment of the hazardous metals within the glass-ceramic matrix so that the waste form will conform to the toxicity characteristic leaching procedure [19] and pass the product consistency test [20]. With limited conceptual design funding, waste-form testing to date includes laboratory tests of three common, bounding types of calcine: sodium-bearing waste, aluminum, and zirconium. Thus far, waste-form testing has shown the ability to contain the hazardous metal constituents in calcine except for cadmium—a RCRA hazardous metal. However, the sodium-bearing waste recipe passed all tests and the zirconium recipe has contained about 80 to 90% of the cadmium. Figure 1 provides photographs of the test samples made during waste-form testing. The mitigation plan being followed to eliminate this failure mode involves adjustment of additives to immobilize all of the characteristically hazardous metals in calcine.

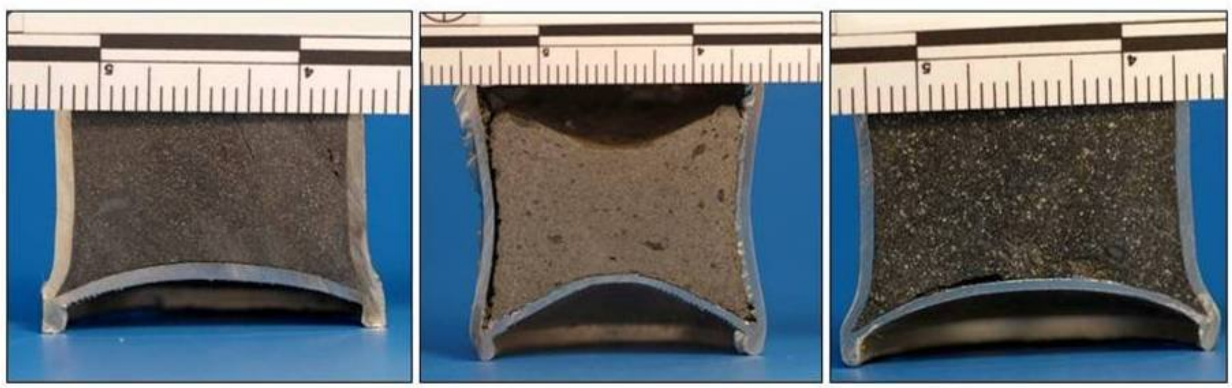

Fig. 1. Cross sections of glass-ceramic waste forms produced during testing from aluminum calcine (left), zirconium calcine (center), and sodium-bearing waste calcine (right).

<u>Reliability, Availability, Maintainability, and Inspectability Analysis</u>

Similar to FMEAs, reliability, availability, maintainability, and inspectability (RAMI) analysis is a technical risk assessment tool that allows management to access individual system readiness levels through review of system spreadsheets, parameters, and other quantitative data to provide better direction for resource allocation. Reliability is the continuity of correct operations and is determined through testing. In simple terms, it is the percent of time producing within specifications. Availability is the readiness of continuity of operations and is measured as the mean time before failure. Maintainability is the ability to undergo maintenance and repairs and is measured as the mean time to repair. Inspectability is the ability to measure system performance. During conceptual design of the Calcine Disposition Project, values for these parameters were estimated with reliance on project technical expertise and use of vendor data, industry standards, and other source documents. As the design process progresses and testing is performed on the systems of the process, the values will be adjusted as necessary. As with FMEAs, mitigation plans are established for systems and subsystems that require more sophisticated RAMI evaluations. The ultimate goal of a RAMI analysis is to obtain information that allows for more accurate decision making.

Time and Motion Study

Data generated from FMEAs and RAMI analyses were incorporated into a time and motion model using the ExtendSim software tool [21]. The model was used to verify and validate that the HIP-treatment process will be completed within the schedule requirements documented in the 1995 Idaho Settlement Agreement [4]. Time and motion studies are a method of measuring productivity by breaking down a complex process into small, simple steps. The time durations required for each step, along with the RAMI parameters discussed previously, are input to the model to obtain an overall duration of the project. During conceptual design, similar to RAMI parameters, time durations are generally estimated. Again, as the design process advances and better testing data are obtained, the time durations will be modified to obtain more precise estimates. Because of the projected length of the project, with its numerous operational stages, operational data also will be used to refine the time and motion model.

Mass and Energy Balance Model

A mass and energy balance model was developed using AspenPlus software [22]. This model was used to assist in the design of process equipment and piping, determine material flow properties, and estimate process emissions. The model makes use of software-specific modules that are combined to simulate the overall process. As part of the permitting process, estimates of atmospheric emissions must be made. The mass and energy balance uses process parameters to perform these estimations.

DISCUSSION

Functional Analysis

As noted in the Introduction, the Calcine Disposition Project is organized into five functional areas. Figure 2 presents the project's simplified process flow diagram with systems identified. This diagram provides an overview of the process systems that may be used with the functional area descriptions provided below.

The retrieval functional area (SEN 5) comprises the existing Calcined Solids Storage Facilities (SEN 5.1), the retrieval system (SEN 5.2), the transport and surge system (SEN 5.3), the feed canning system (SEN 5.4), the process off-gas system (SEN 5.5), and retrieval remote design, maintenance, and tools (SEN 5.6). Overall, this functional area transports the calcine from its current location in the calcine storage bins and packages it into the HIP cans. These activities include retrieval of the calcine from the calcine storage bins, heating the calcine to decompose the nitrates, mixing the calcine with additives to immobilize hazardous metals in the waste form, and filling the HIP can with the mixture.

The treatment functional area (SEN 6) comprises the HIP can system (SEN 6.1), HIP furnace system (SEN 6.2), HIP system (SEN 6.3), and treatment remote design, maintenance, and tools (SEN 6.4). Overall, this functional area converts the HIP can filled with a granular HIP mixture into a monolithic solid waste form. The treatment functional area consists of loading the HIP can into a HIP furnace and subsequently loading the HIP furnace into the HIP machine. The HIP machine uses high temperature argon (1,000 to 1,250°C [1,832 to 2,282°F]) to apply isostatic pressure (50 to 100 MPa) to create a monolithic glass-ceramic waste form.

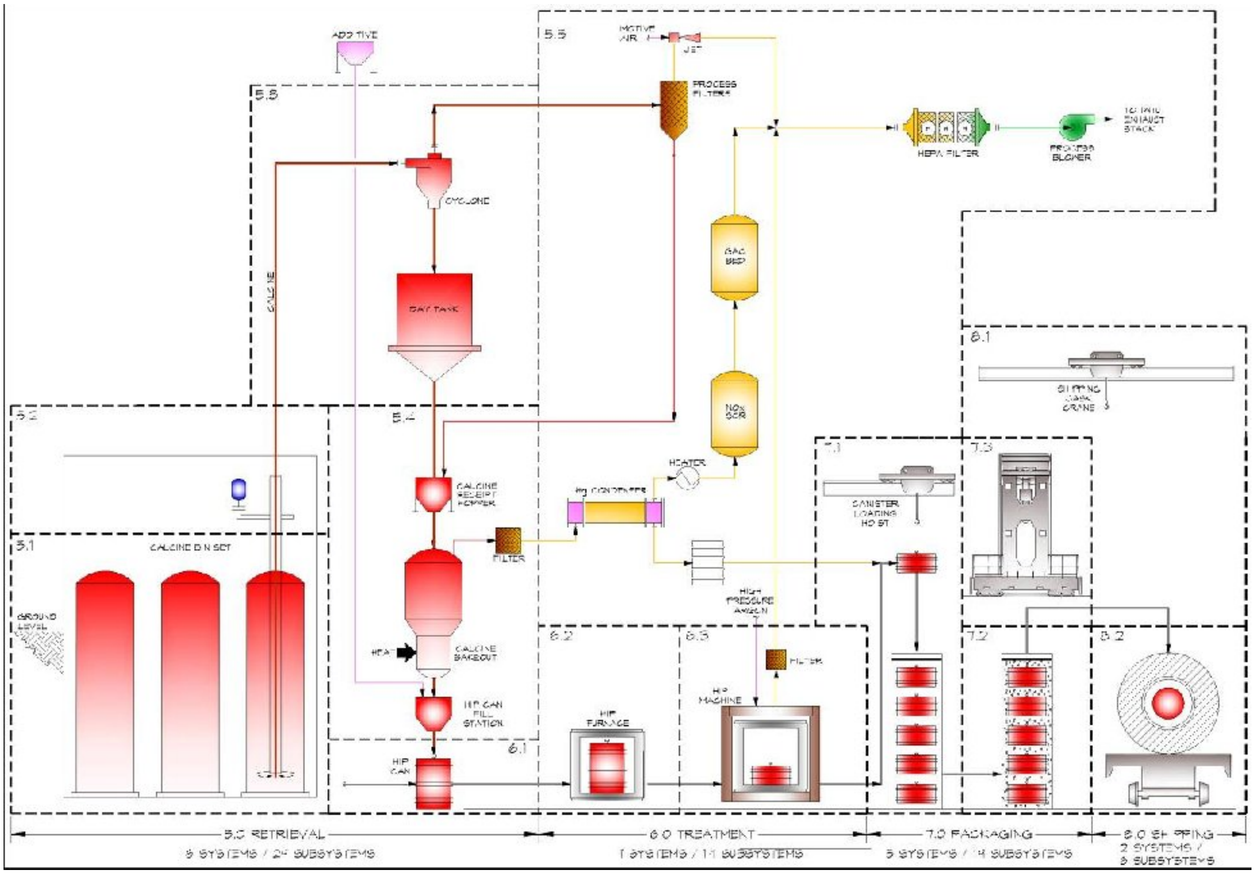

Fig. 2. Calcine Disposition Project simplified process flow diagram.

The packaging and handling functional area (SEN 7) comprises the canister loading system (SEN 7.1), canister staging system (SEN 7.2), cask loading system (SEN 7.3), in-cell transfer system (SEN 7.4), and packaging remote design, maintenance, and tools (SEN 7.5). Overall, this functional area includes the processing steps from receipt of the HIP-treated waste cans to completion of a transportation package for shipment. This functional area also includes transport of HIP cans, HIP furnaces, and HIP canisters throughout the hot cell area.

The shipping functional area (SEN 8) comprises the shipment loading system (SEN 8.1) and the shipping package transportation system (SEN 8.2). Overall, this functional area includes the processing steps from receipt of transportation packages for shipment trough transport of the package by rail to the INL Site boundary. This functional area also includes completion of the design of the transportation package, rail cars, and rail lines to the INL Site boundary.

The plant facility and support functional area (SEN 9) is described in the sections below.

Calcined Solids Storage Facilities Overview

As stated in the Introduction, calcine is stored in Calcine Solids Storage Facilities 1 through 6. A seventh calcine storage facility was built but never placed into service. The calcine storage facilities are of varying designs, containing from three to 12 stainless steel bins per facility for a total of 43 bins within the six facilities storing calcine. Each bin set is housed in its own concrete vault. The bins range from about 6.1 to 20.8 m (20 to 68.2 ft) in height. Calcine generation dates from 1963 for the oldest calcine in Calcine Solids Storage Facility 1 to 2000 for the newest calcine in Calcine Solids Storage Facility 6. Figure 3 is an illustration of the facilities, the individual bin sets, and the volumes of stored calcine within them.[14]

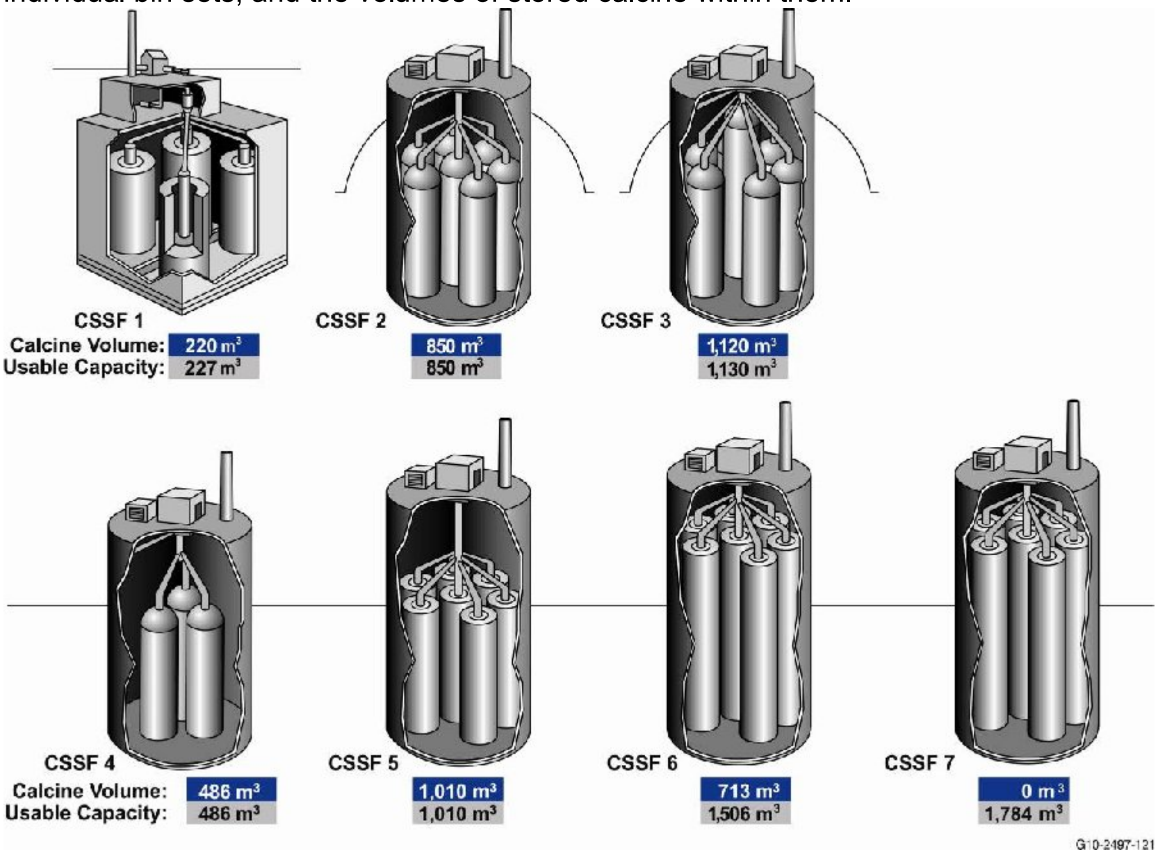

Fig. 3. Illustration of stored high-level waste calcine volumes by individual Calcine Solids Storage Facility (CSSF) [adapted from 23].

HIP Treatment Facility Overview

The facility built to accomplish the Calcine Disposition Project mission is the existing Integrated Waste Treatment Unit facility, which will be modified for HIP treatment and include a new addition for packaging and shipping on the east side of the existing facility. Additional buildings and structures such as the Shipment Wash and Inspection Building, the HIP Electrical Building, and exterior equipment pads will be part of the Calcine Disposition Project facility. The calcine-treatment facility will be a nonreactor HLW nuclear facility that, based on a hazard categorization evaluation, has received a preliminary classification of Hazard Category 2 [24].

The project conceptual layout (see Figure 4) is based on the concept of using the existing Integrated Waste Treatment Unit hot cells as the leading process cells for the calcine-treatment facility. A shielding wall will be added to the larger of the existing steam reformer cells to provide a total of three cells in which the HIP treatment machines will be located. Existing sodium-bearing waste canister fill cells to the east of the HIP cells will be re-used as HIP can fill and sealing cells. This will be the location where the HIP cans are filled with the calcine/additive mix and then evacuated and seal welded in preparation for HIP treatment. The center fill cell will be modified to provide an operation corridor to allow for operation and maintenance of the fill cells.

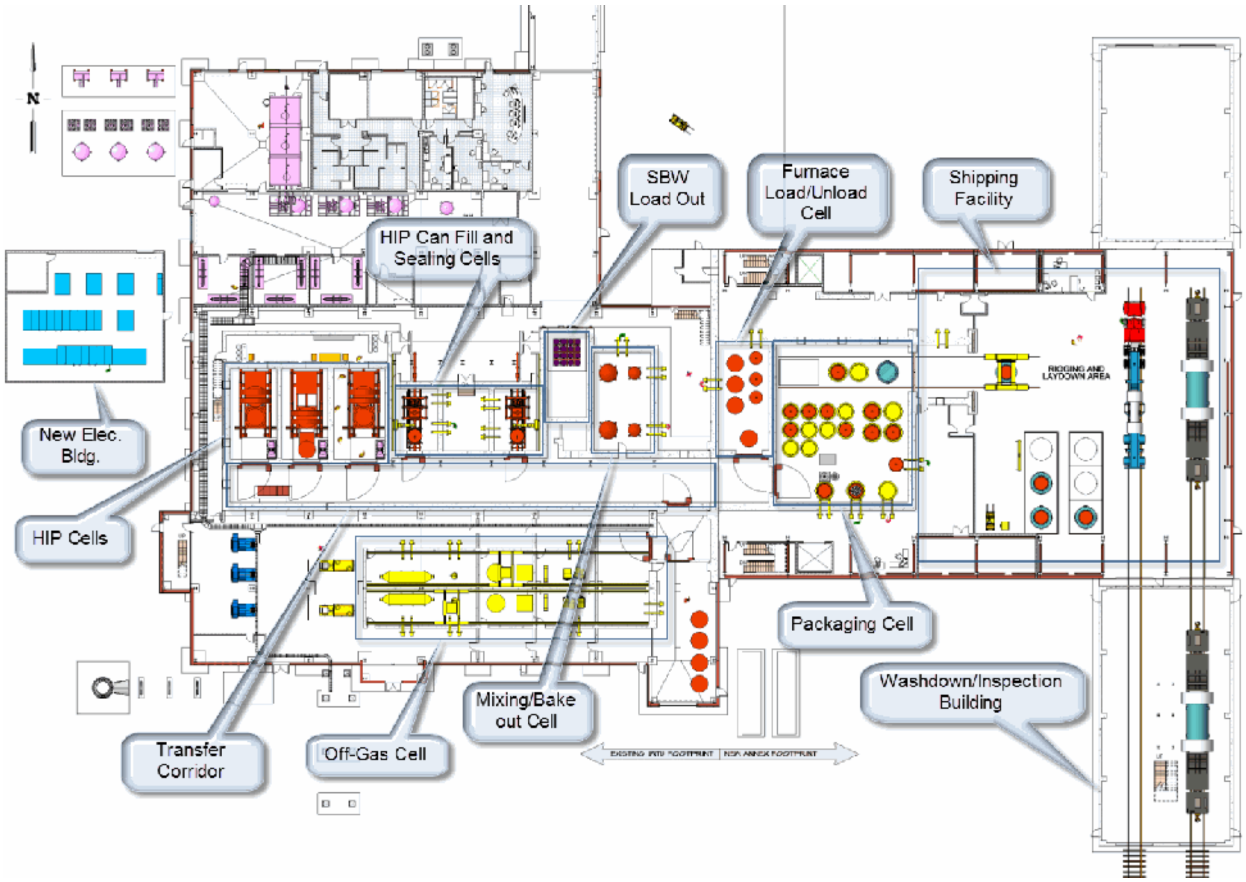

Fig. 4. Conceptual layout of Calcine Disposition Project facility.

The existing sodium-bearing waste loadout function with the shielded bell crane will remain to allow for shipping of the sodium-bearing waste canisters or potential HIP treatment of the remaining sodium-bearing waste at the conclusion of the HIP treatment process. To the east of the sodium-bearing waste loadout is a new mixing and bakeout cell. This cell allows for the calcine to be received from the Calcined Solids Storage Facilities, mixed with additive, and baked out to remove moisture and nitrates. Once the calcine mix has been baked out, it is then pneumatically transferred to the HIP can fill cell.

Once the HIP cans are filled and sealed, they are transported down the transfer corridor and into the HIP furnace load/unload cell and placed into the HIP furnace. They are then HIP treated in the HIP machine and returned to be unloaded from the furnace. An operating corridor has been located between the mixing and furnace loading cells to allow for electromechanical manipulators and operators. Once the HIP cans are unloaded, they are transported into the new packaging cell.

At this point, the HIP cans are loaded into canisters, voids are filled with stabilization media, and then welded within the packaging cell. The canisters are then surveyed, weighed, and loaded into a shipping cask, which enters the cell from the shipping area. A large gantry crane will be used to transfer the shipping cask into the packaging cell through an airlock.

The shipping area is a large high-bay facility with an overhead crane for unloading the shipping casks from rail cars and moving the casks within the facility. It allows for two rail cars to enter the facility through the inspection and washdown bay, where the rail cars will be washed to remove grime or other debris before entering the facility. The casks will then be unloaded from the rail cars and returned to the cars once the canister has been loaded in the cask. At this point, the casks are returned to the inspection bay and inspected before leaving the facility. The shipping area will allow for sodium-bearing waste shipment by being able to accommodate entrance of a semi-truck into the facility, loading of the sodium-bearing waste casks, and egress through the truck airlock to the north.

CONCLUSION

The Calcine Disposition Project systems engineering approach, including use of industry-proven design-for-quality tools and quantitative assessment techniques, has strengthened the project's design capability to meet its intended mission in a safe, cost-effective, and timely manner. Use of these tools has been particularly helpful to the project in early design planning to manage variation; improve requirements and high-consequence risk management; and more effectively apply alternative, interface, failure mode, RAMI, and time and motion analyses at the earliest possible stages of design when their application is most efficient and cost effective. The project is using these tools to design and develop HIP treatment of highly radioactive calcine to produce a volume-reduced, monolithic waste form with immobilization of hazardous and radioactive constituents.

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