WASTE VITRIFICATION SYSTEMS LESSONS LEARNED

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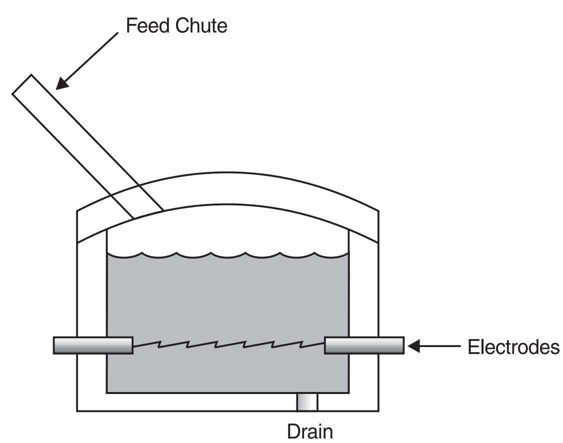
EXECUTIVE SUMMARY

This report presents experience with the vitrification of both high level and low level radioactive waste within DOE, the United States industry, and at the British Nuclear Fuel, Limited vitrification facility in Sellafield, England. This report was prepared by the Office of Environment, Safety and Health, at the request of Department of Energy (DOE)-Fernald to present lessons learned in the design and operation of waste vitrification systems. This information is particularly important to the Fernald Environment Management Project (FEMP) as it considers the path forward in vitrification of radium-bearing K-65 residues contained in Silos 1 and 2 at the site. The information is also pertinent to the DOE community for current and future vitrification projects.



Joule–Heated Melter

Production-scale vitrification efforts within DOE have been restricted to a single technology, Joule-heated melters. Joule-heated melting is a mature technology that has been successfully applied in the glass-making industry, and is used within the DOE complex to immobilize radioactive waste materials. It involves heating the glass in a melter by conducting electric current through the glass matrix.

Within DOE, two Joule-heated melter campaigns for high level waste vitrification have already been successfully carried out, each with a different waste matrix. The Defense Waste Processing Facility (DWPF) at the Savannah River Site (SRS) near Aiken, South Carolina has processed 555 canisters of radioactive glass as of January 21, 1999; West Valley Demonstration Project (WVDP) near Buffalo, New York has vitrified over 232 canisters of waste. These successes, along with strong support from the scientific community, led to consideration of Joule-heated melter technology for four new low-level waste vitrification efforts – radium-bearing K-65 residues at Fernald; M-Area electroplating sludge at Savannah River; low level waste treatment at Hanford; and the construction/testing of a transportable large-scale melter in Oak Ridge.

Because the Joule-heated melter technologies for processing high level and low level radioactive wastes are similar, lessons learned were drawn from experiences of both.

Low Level Waste Vitrification

- Fernald Vitrification Pilot Plant
- Savannah River Site Vendor Treatment Facility
- Oak Ridge Transportable Vitrification System
- Hanford Low-Level Vitrification Project

High Level Waste Vitrification

- Savannah River Site Defense Waste Processing Facility
- West Valley Demonstration Project Vitrification Facility
- Sellafield, UK Waste Vitrification Plant
- Savannah River Stir Melter

Project-Specific Experiences and Lessons Learned

Many of the waste vitrification projects experienced glass leakage, cracks or damage in the refractory, uncontrolled high temperatures or hot spots, instrumentation failures, and chronic blockages of the glass pouring streams. Specific experiences and lessons learned follow for five of the eight projects discussed in this report. The other three projects had fewer relevant lessons learned either because of the waste stream, small scale of the project, or reluctance of the vendor to reveal lessons learned due to the proprietary nature of the project.

Fernald Vitrification Pilot Plant had technical and operational problems throughout its campaigns, particularly in maintaining temperature control within the melt pool. Following a December 26, 1996 event in which glass breached the bottom of the melter, the melter was shut down pending management decisions regarding future treatment of the silo wastes. Some of the problems encountered during the campaigns included: cracks in the refractory around the discharge orifice and in the E-brick walls, clogging of the frit feed tube and discharge orifice, leakage of various cooling jackets, high temperatures and stray electrical currents in the areas of the bottom drain, and lack of correlation between instrumentation indications and actual conditions. From these experiences, several lessons learned or recommendations, most of which are related to design, were formulated. They include:

- Select a design that minimizes or eliminates refractory penetrations
- Evaluate materials of construction for form, fit, reaction to each other, and life expectancy
- Evaluate and improve the reliability of the melter discharge chamber
- Improve reliability of temperature monitoring and level indicators and incorporate ground current monitoring in the melter design
- Incorporate redundant back-up and support systems, such as airflow indicators, bubblers, and sensors
- Consider generic implications of material failures of components
- Consider alternate melter designs, such as gas low-temperature or electrical

Savannah River Site Vendor Treatment Facility experienced molten liquid leakage on three occasions. On May 17, 1996, molten liquid leaked from the refractory assembly during non-radioactive startup testing. The feeding of anhydrous borax (a glass-forming agent) directly to the melter when the melter was at high temperatures (1000^{o}C) resulted in the borax migrating, causing electrical shorts, localized Joule heating, and damage to the refractory. On June 13, 1996, glass leaked from the bottom drain plug, and on August 1, 1996, leakage through the inner shell was observed, but there was no release from the outer shell to the environment. Also, problems with hot spots were pervasive in March 1997. When the hot spots could not be cooled, the vendor shut down operations to analyze failures and undertake facility modifications. Many of the lessons learned identified by GTS Duratek are currently deemed proprietary. However, some specific actions or lessons learned could be drawn from the leakage event, including:

- Refrain from adding anhydrous borax, consider glass frit
- Prevent electrical shorts between the electrodes and the inner shell, and lower the temperature of the inner shell by removing some fiber insulation between the inner and outer shells and enlarging bus openings on the outer shell
- Reduce the voltage potentials that caused the Joule heating by converting the melter from a two-phase to a single-phase melter

Oak Ridge Transportable Vitrification System is a large scale pilot plant for demonstrating treatment of low level radioactive mixed waste in the form of sludge, soils, incinerator ash, and other waste streams. On November 5, 1996, the vitrification system experienced glass leakage from the melter to the subfloor of the melter module, burning cooling hoses, power cables, and instrument wiring. The cause of the leak was failure to maintain adequate compression of the refractory joints when the melter was thermally cycled. The vendor manual requires that binding bolts be loosened as refractories expand during heating of the melter, and tightened as the melter cools. It is unclear whether the binding adjustments were made during each thermal cycle or if the existing design and procedures were adequate. The operational event resulted in the following lessons learned:

- Consider modifying the refractory binding system and operating procedures
- Plan operations to minimize thermal cycling
- Reroute hoses, cables, and instrumentation wiring away from potential leak areas
- Review operator training and qualification
- Develop a "pre-fire plan" and additional emergency procedures
- Ensure that guarding installed for personnel protection do not inhibit access for necessary observations, adjustments, and emergency actions

The SRS Defense Waste Processing Facility began cold chemical runs in October 1992, after 20 years of development and construction. On April 3, 1993, an unplanned excessive vacuum was drawn on the melter during cold chemical runs. The vacuum caused water to move from the seal pot to the melter. Investigations concluded that the necessary programs to support transition from construction to operations were not effectively implemented. After glass pouring began, problems developed with the stability of the glass pouring stream, which caused the glass to accumulate in the lower pour spout and bellows area and requiring significant effort to clean. The problem was caused by erosion of the upper knife edge of the pour spout. In addition, weld corrosion of the piping for the cooling water system caused some stainless steel piping welds to exhibit exterior evidence of corrosion. The corrosion was microbiologically induced. Some lessons learned include:

- Evaluate system design for adequate vacuum protection for systems or components, especially when positive displacement pumps or blowers are used
- Avoid relying on operator actions or administrative controls to mitigate events that can occur faster than the operator's ability to respond
- Minimize composition and temperature variations of, and deposits in, the pour spout that may cause changes in the physical properties of the pouring glass
- Include recent and complete information on environmentally induced problems, such as microbiological induced corrosion, in basic design and safety analysis reports
- Include, and comply with, water quality requirements in design specifications

West Valley Demonstration Project Vitrification Facility underwent radioactive operations in June 1996, after a five-year system functional and checkout test, and process trials in a scaled-down nonradioactive pilot plant. During integrated cold operations, the seal weld between the melter dam and trough failed due to localized high stresses during initial melter heat-up.Upon investigation, it was determined that the design drawings did not specify reinforcing gussets, due to a drawing transposition error. In November 1996, waste slurry flowed into a compressed air supply pipe. Three workers and part of the operating isle were contaminated during the subsequent repair operations to replace the contaminated pipe section. In January 1997, elevated levels of airborne contamination were detected in an operating aisle outside the vitrification cell. Melter pressure spikes transported the contamination from the melter along conduits for the discharge heater power supply. Maintaining melter pressure control has been a recurring challenge for this project because of the irregular off-gas flow characteristics and the pulsing action of the feed pump. Additionally, the melter experienced chronic blockages in the glass pour stream prior to radioactive operations. Blockages during startup testing resulted from a failed barrier between the melt chamber and discharge chamber. Blockages after melter repairs were due to excessive accumulation of very thin glass fibers. A few of the many lessons learned include:

- Improve radiation protection, operating procedure compliance, and conduct of operations
- Evaluate conduit penetrations and ensure that pressurization of the conduit is prevented by venting or installing effective barriers
- Install a high-speed data acquisition system and quick-acting control valve to make melter pressure control more manageable
- Reduce angel hair formation by installing a flow reducing orifice, thereby limiting the airflow through the discharge chamber

General Lessons Learned

Some general observations and lessons learned are also assembled. A few of these include:

- Unique operational issues, such as excessive corrosion of parts, preventive maintenance, and system inspections, need to be considered in the design of vitrification systems.
- Periodic evaluations of critical components for overall effective operations should be made during all phases, including design and operation. During the design phase, all components (i.e., thermal walls, air lifts, bubblers) should be evaluated for consequences of potential failure.
- Materials for melter construction must be selected for compatibility with wastes.
- A dye penetrant or other non-destructive examination should be performed on critical welds before and after surface finishing
- Operations should be planned to minimize thermal cycling. Due to the high temperatures of operation, such cycling could result in adverse effects such as refractory damage and melter joint expansion.
- The resistance to leaching will vary by glass composition and should be tested across the range of probable waste composition to achieve the desired leach resistance.
- If the feedstock has large amounts of inorganic salts, especially sulfates, chlorides or fluorides, corrosion testing should be conducted to make certain that the salts will not deteriorate the electrodes.

Two other important concerns, which were learned during the preparation of this report, relate to operational safety and project management. First, DOE needs to include worker and process safety as well as nuclear safety (in addition to performance, cost and regulatory compliant schedule) in evaluating and ranking the merit of a technology. This is particularly true for high temperature treatment processes. This operational safety should be an evaluation factor during pilot scale testing and other small scale testing phases.

Secondly, vitrification technical problems notwithstanding, problems have been experienced with project management control in some of the low level waste vitrification projects. The need for a highly disciplined project management system for vitrification projects is evident. Such a system should include the participation of vitrification experts from the start of project planning through plant design, construction, and operation. It should also incorporate contract mechanisms that impose more responsibility and accountability on the vitrification vendors than in the past. Additionally, in light of continuing pressure to lower the DOE cleanup budget and the relatively high cost of vitrification systems, it is critical that detailed knowledge of the technology be assembled, centralized, and readily available to decision makers.

Conclusions

This report presents information in occurrence reports, other documents, and insights from waste vitrification projects. The study shows that significant progress is being made in the development and application of melter systems for treating waste forms. It also demonstrates that the vitrification of low-level waste can be complex because of its heterogeneous and organic makeup; thus the planning and management of low-level waste vitrification projects need much of the careful consideration given to high-level waste projects.

Many other problems and issues remain in the vitrification of radioactive waste and significant lessons learned are evolving. A more detailed study is planned, as Phase 2 of this project, that incorporates root cause analyses, investigates operational safety, and broadens to encompass other waste treatment technologies and cost/benefits. A lessons learned workshop with domestic and international experts is also planned.

WASTE VITRIFICATION SYSTEM LESSONS LEARNED

1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this report is to provide feedback to the DOE complex from experience with vitrification of high and low level radioactive waste. This report was prepared at the request of the Department of Energy (DOE)-Fernald to present lessons learned from selected vitrification facilities in processing radioactive wastes. DOE Fernald is particularly interested in experiences with vitrification as it considers the path forward in processing radium-bearing K-65 residues in Silos 1 and 2 at the site. This report presents information on the performance of vitrification systems within the DOE complex and abroad (limited to British Nuclear Fuel, Limited (BNFL) vitrification facility in Sellafield, England). The lessons learned address the health and safety, construction, operation, and decontamination and decommissioning experience with vitrification projects. Because vitrification technologies for processing high level and low level radioactive wastes are similar, lessons were drawn from experiences of both.

1.2 OBJECTIVES

The objectives of the report are to:

(1) provide a data source on waste vitrification systems;

(2) identify the common issues and problems with vitrification systems as a function of the types of waste being processed;

(3) provide a compilation of lessons learned during the development and operation of various vitrification systems designed for treating radioactive wastes; and

(4) evaluate analyses of alternatives to vitrification for immobilizing waste.

The information on individual vitrification systems, contained in Chapters 4 and 5 of this report, address objective (1) above and was developed from occurrence and investigation reports, briefing materials, verbal communications, and other information provided for the individual facilities by their points of contact. The second and third objectives are addressed primarily in Chapter 3 of this report, which represent a culmination of Chapters 4 and 5. The fourth objective will be covered in Phase 2.

1.3 SCOPE

This report is the first of two phases of a vitrification lessons learned study. Phase 1 is focused on vitrification system melters, specifically the Joule-heated melters. Phase 2 will address the other types of vitrification technologies in greater detail as well as alternate waste treatment technologies.

2.0 BACKGROUND

2.1 VITRIFICATION TECHNOLOGIES

Vitrification is an emerging technology within the DOE complex that uses a heat source (usually resistance heating) to create a molten bath of glass-forming materials into which waste materials can be dissolved to become an integral part of the glass. In the process, organic compounds are destroyed (by the high temperatures), and when the glass product cools and solidifies, any contaminants that were not destroyed or volatilized are immobilized. Vitrifiers are essentially furnaces adapted from the glass-making industry, with the process modified to accommodate the type of waste stream desired to be vitrified.

Several types of vitrification processes have been demonstrated or used in DOE. These include Joule-heated melter, plasma arc centrifuge treatment (PACT) system, plasma hearth process (PHP), American Society of Mechanical Engineers (ASME)/ United States Bureau of Mines (USBM) arc melter furnace, and in-situ vitrification. Of these, only Joule-heated melters have been used on a production scale in DOE. Each type of process has different characteristics and produces differing amounts of contaminant levels in the off-gas, which influences the relative need for further waste treatment and waste processing. A key characteristic of all vitrification processes, is that they immobilize contaminants in a solid waste form. Additionally, vitrification processes an end-product with a greatly reduced volume when compared to the volume of the input material. This significantly reduces the packaging, transportation, and disposal requirements and costs, and therefore provides a major incentive for the highest volume reduction performance.

The method of heating is the principle that distinguishes the various vitrification technologies. Joule-heated melters are heated by a current passed through the glass-forming materials. Plasma arc melters use plasma torches to generate extremely high temperatures. Combustion melters burn fuels to generate heat. Graphite arc furnaces generate heat by a spark passing from a graphite electrode to either the material to be melted or another electrode. Bushing melters use metal screens as electrical resistance elements, which heat chemicals to form molten glass.

Joule-Heated Melter

The Joule-heated melter furnace incorporates a process of heating the glass by conducting electric current through the glass matrix. Figure 1 shows a simplified diagram of the Joule-heated melter, more detailed drawings are contained in Chapters 4 and 5. In a Joule-heated melter, vitrification is done in a single-step process. Both the waste concentrate and the glass former (including glass frit) are directly introduced into the melting chamber, thus forming a process zone where the glass melting reactions occur. The melter is the primary component of the vitrification process in the Joule-heated process. The melter is a water-jacketed stainless steel box insulated by multiple types of refractory with separate cavities for glass melting and pouring. Initial heat-up of the melt cavity is started by application of natural gas burners or

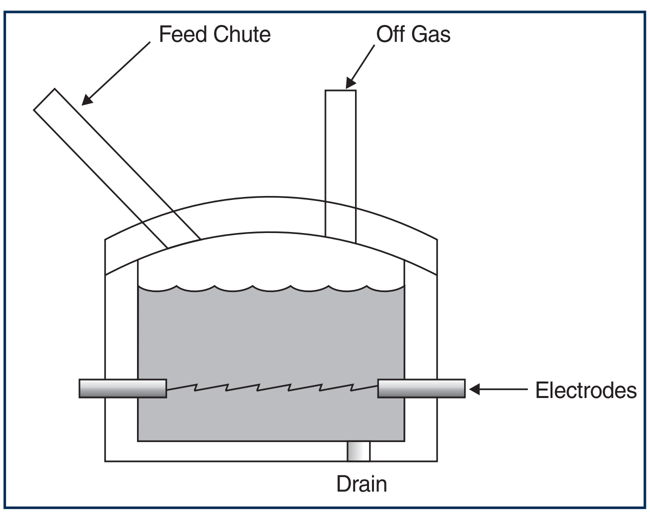


Figure 1. Simplified Diagram of Joule–Heated Melter

electric heaters above the glass pool. Joule-heating, using alternating current through the melter electrodes, begins between 600°-700°C and rises to approximately 1100°C for vitrification. Various electrode arrangements exist, and some erode far less than others. Molten glass, unlike vitreous glass, has a low dielectric constant and will pass large currents.

Plasma Arc Centrifuge Treatment (PACT)

Plasma arc vitrification occurs in a plasma arc centrifugal system where heat transferred from a plasma arc torch creates a molten bath. Solids are melted into the bath while organics are evaporated and/or pyrolized and partially oxidized. Metallic feed material can either form a separate liquid phase underneath the metal oxide slag layer or can be oxidized and become part of the slag layer.

Waste material is fed into a sealed centrifuge where a plasma torch heats solids to approximately 1760°C and gas headspace to a minimum of about 1000°C. Organic material is evaporated and destroyed. Off-gases travel through a gas-slag separation chamber to a secondary chamber where the temperature is maintained at over 1100°C for at least two seconds for complete oxidation. The off-gases then flow through a standard off-gas treatment system.

Inorganic material is reduced to a molten phase that is uniformly heated and mixed by the centrifuge and plasma arc. Additives can be introduced in-process to control slag quality. When the centrifuge slows, the molten material is discharged as a homogenous, glassy slag into a mold or drum in the slag collection chamber. When cooled, the resulting product is a non-leachable, glassy residue that meets the Environmental Protection Agency (EPA) Toxicity Characteristics Leaching Procedure (TCLP) criteria.

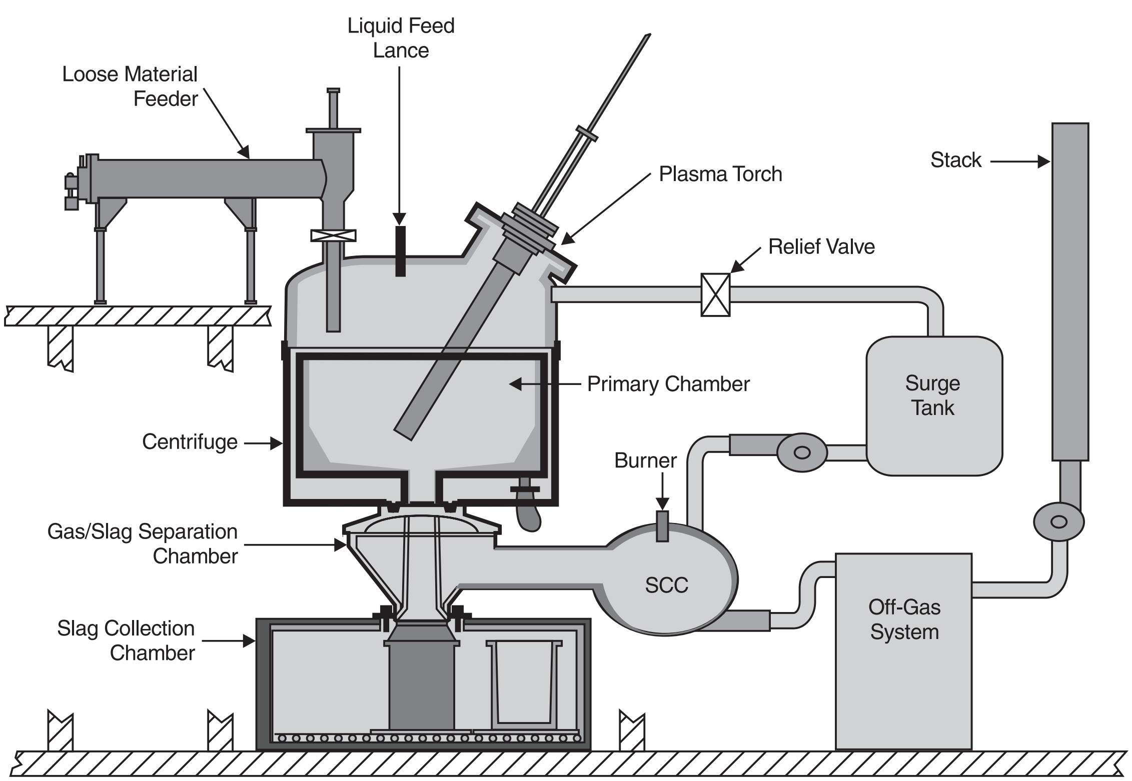


Figure 2. PACT Melter

The entire system is hermetically sealed and operated below atmospheric pressure to prevent leakage of process gases. Pressure relief valves connected to a closed surge tank provide relief if gas pressures in the furnace exceed safe levels. Vented gas is held in the tank, then recycled through the PACT system. The off-gas treatment system removes particulates, acid gases, and volatilized metals.

The technology has been demonstrated under the EPA superfund innovative technology evaluation (SITE) program and has processed waste forms including mixed LLW and typical organic and inorganic solid and liquid wastes. It is important to note, however, that this melter is not omnivorous; therefore, rigorous attention must be given to feedstock preparation requirements. Figure 2 shows a schematic of the PACT melter by Retech Corporation.

Plasma Hearth Process (PHP)

PHP is a fixed hearth furnace that operates in substoichiometric mode (use of less than normally required oxygen for waste treatment). The plasma arc torch of PHP is located in the primary chamber. The PHP system currently being developed for DOE mixed waste treatment consists of the following five subsystems:

(1) waste feed system,

(2) primary reaction chamber,

(3) secondary combustion chamber

(4) air pollution control system, and

(5) slag removal system.

Drummed waste is fed to the primary reaction chamber, where heat from the plasma torch initiates a variety of chemical and physical changes. Organic compounds in the waste are decomposed, volatilized, pyrolized, and/or oxidized. The remaining inorganic material, including the drum, is heated until it melts and separates into

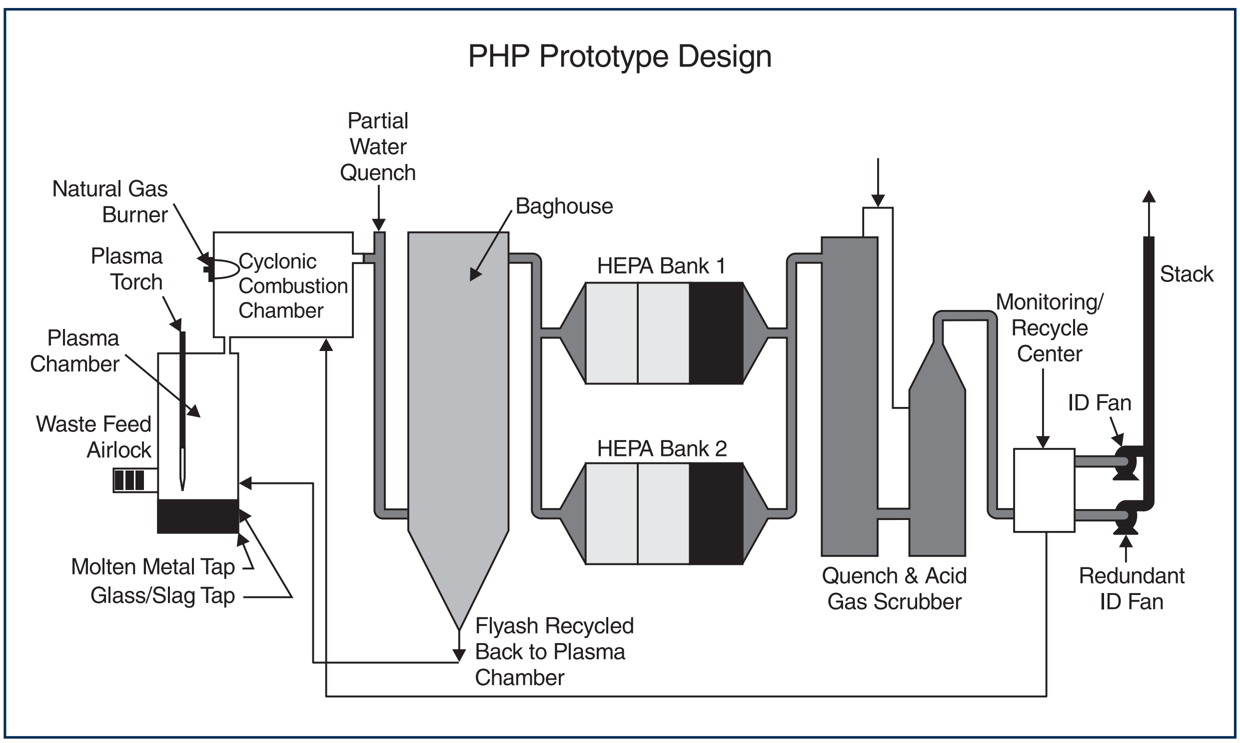


Figure 3. Plasma Hearth Process Vitrification Technology

molten slag and metal phase. Actinides and oxidized heavy metals migrate to the slag phase. Cooling and solidification of this material results in a high integrity final waste form. Off-gas from the primary reaction chamber is transported to a secondary combustion chamber for further combustion to ensure complete conversion of organic compounds to CO_2 and water. The off-gas is cleaned using conventional technologies capable of achieving a very high degree of removal of principal organic hazardous constituents (POHCs). Figure 3 shows a schematic prototype design of a Phase 3 PHP system.

Arc Melter Furnace

This vitrification system also utilizes a plasma arc furnace to pyrolyze combustible organic material and melt residual inorganic materials with an electric arc. The ASME/USBM MVA developed this plasma furnace, which contains three carbon electrodes, a continuous feed system, and an off-gas treatment system with slag and metals trapping capability. The side wall is cooled from a slag layer on the refractory lining. This further protects the refractory from degradation. The resulting molten slag, upon cooling, produces a demonstrated durable vitrified cast form that meets the TCLP criteria.

The melter has been used to treat a variety of waste containers and waste matrices comprised of both hazardous and radioactive material. The key advantage of the arc melter furnace is its ability to process a wide variety of heterogeneous waste into a non-leachable final product. The existing off-gas system can be modified for transuranic (TRU) and heavy metals.

In-Situ Vitrification (ISV)

ISV is a waste treatment technology that uses electrical power to melt in situ contaminated earthen media such as soil, sediment, and mine tailings. The process permanently destroys, removes, and/or immobilizes hazardous and radioactive contaminants contained in the media. The ISV process is initiated by formation of a pool of molten soil at the surface of a treatment zone between four electrodes. The molten soil serves as the heating element for the process, wherein electrical energy is directly converted via Joule heating as it passes between the electrodes. As power continues to be applied, the molten mass grows outward and downward, thereby creating individual batch melts of up to 1,000 tons. Melt temperatures are in the range of 1500^o-2000^oC. Off-gases are collected in a containment hood and routed to a treatment system. When the desired treatment volume has been processed, power is shut off and the molten mass solidifies into a glass and crystalline mass.

2.2 PERFORMANCE EXPECTATIONS

The performance expectations for a waste vitrification plant fall into two principal categories: technical performance and cost/schedule performance. A fundamental expectation for any vitrification system is the technical performance of the final solidified waste form. There are five major areas of interest related to waste form performance:

- Flexibility/waste compatibility
- Mechanical integrity
- Thermal stability
- Radiation effects
- Chemical durability

Chemical durability is generally considered the most important of these technical properties.

One of the most important factors relative to cost/schedule performance is the ability of a vitrification system to routinely and reliably meet technical performance expectations.

3.0 RECURRING PROBLEMS AND COLLECTIVE LESSONS LEARNED

3.1 DOE EXPERIENCE

Although vitrification processes are proven to be effective in the treatment of waste streams, implementation of this method of treatment requires careful consideration and an appreciation of the difficulties associated with formal implementation. All successful vitrification systems, which include the West Valley Demonstration Project (WVDP), Defense Waste Processing Facility (DWPF), and Sellafield, UK-Waste Vitrification Plant (WVP), had effective pilot demonstration vitrification plants prior to full scale development. In addition, even the pilot plant failure at Fernald provided useful information to the Department prior to building the full scale melter.

Common Problems

Experience with vitrification systems at DOE sites has demonstrated that, while many difficulties are specific to the system at hand, there are a number of factors common across the complex. Many of the melter performance problems can be traced to design deficiencies and material compatibility problems. The following is a list of the common problems encountered in this area.

- Inadequate design considerations for maintenance and surveillance
- Lack of a comprehensive failure modes and effects analysis
- Lack of a systems engineering analysis on design and construction
- Leakage through penetrations of the melter shell(s) and liner (for instrumentation, drains, etc.). These are typical weak spots, and their number and placement need to be carefully controlled, as does their design and finishing.
- Clogging, often severe, of the melt (product) discharge orifice, caused by excessive cooling of the melt as it reaches that point. Changes in the direction of flow of the melt at or approaching the discharge can also be a contributing factor. (This will be an agenda item for the Phase 2.)
- Low reliability of critical support systems including cranes, water cooling systems, remote mechanical equipment, and maintenance support systems. (This will be an agenda item for the Phase 2 under the subject of matching components/peripherals to the operating environment.)
- Corrosiveness of the waste materials, especially where electrodes are concerned in Joule-heated melters. This suggests that laboratory-scale corrosion tests using samples of the waste to be vitrified should be performed.
- Incompatibility of the refractory lining materials for the melter with the waste/glass-forming materials.

Following this discussion, Table 1 provides the cumulative lessons learned for LLW vitrification system performance, and Table 2, for HLW performance. The two tables categorize the lessons learned as design, construction or operations areas.

Procurement and Construction Considerations

Procurement of vitrification systems has historically involved contract types that limit the responsibility and liability of the vendor and incorporates acceptance based on limited testing with waste surrogate materials. Thus, the vendor has little or no responsibility for melter performance under actual operations; that is, a melter can be deemed acceptable long before it has to produce the actual end-product. Mutually agreed upon performance-based contract vehicles should be used.

If the melter is not installed/erected by the melter vendor, the melter contract should require that the erection contractor be fully trained by the vendor. Further, all melter erection activities should be under the direct supervision of the vendor; that is, the vendor should be fully responsible for correct assembly and erection of the melter.

System Performance Testing and Turnover/Acceptance

No vitrification process/system can be deemed acceptable until it successfully produces the product for which it was acquired. Therefore, each DOE site that enters into any type of contract arrangement for a vitrifier should precisely define the waste stream to be treated, the form of the end-product, and the testing that will be done to ensure that the end-product exhibits the desired characteristics. Among the deficiencies evidenced by the current DOE vitrification plants in this regard are the following:

- Reliance on a melter's ability to produce glass when glass is the only input material during testing; and
- Over reliance on surrogate materials for acceptance testing.

To avoid these deficiencies, each DOE site may want to review the experience gained at WVDP where surrogated waste streams have been used to qualify the WVDP's glass recipe.

Operations, Process Controls and Standby/Layup Considerations

One major deficiency identified in the operation of melter systems is excessive start-ups and shut-downs and the resultant effects on melter systems. A significant number of the facilities evaluated have had failures of the refractory material and vessel walls due to molten glass ingress around penetrations. The frequency of heat-up and cool-down appears to correlate with vessel and material confinement integrity problems. The majority of the melter systems reviewed show a significant reduction in life cycle performance attributable to thermal cycling, much of which resulted from the manner in which the melter was operated rather than design problems.

Table 1. Low-Level Waste Vitrification Lessons Learned

Design

- Unique operational issues need to be considered in the design and operation of vitrification systems (i.e., excessive corrosion of parts, required preventive maintenance system inspections).
- Evaluations of "critical components" should be made during all phases, including design and operation. All components (i.e., thermal walls, air lifts, bubblers) should be evaluated for potential failure. All process materials and components should be baselined before start-up along with an analysis of operational procedures, sequences, and casualty procedures. This would minimize abnormal conditions or events.
- Engineering design of vitrification systems needs to consider the catastrophic failure on the operational capabilities of the melter. For example, the routing of cables, hoses, and instrumentation wiring beneath the floor and subfloor made them vulnerable to burning and destruction as a result of a glass leak.

Operations

- Due to the complexity and challenge of vitrification systems, qualification of the project manager needs to be well defined.
- To employ vitrification successfully, schedules need to be established with the recognition that unanticipated hold points may arise due to emergent technical concerns; this would include allowing flexibility in schedule.
- Data quality objectives need to be designed for all data collected for the melters. In addition, adequate analysis time should be factored into the schedule of vitrification system operations.
- Operations should be planned to minimize thermal cycling. Due to the high temperatures of operation, such cycling could result in adverse effects such as damage to refractory, expansion of melter joints, or similar problems.

Table 2. High-Level Waste Vitrification Lessons Learned

Design

- System design must provide adequate vacuum protection for systems or components to prevent migration of materials in case of leakage. This is particularly important when positive displacement pumps or blowers are used.
- Include recent and complete information on environmentally induced problems such as micro-biological induced corrosion (MIC) in the basic design report and the safety analysis report; also, follow design specifications for water quality.
- Review all major design changes implemented on the production melter and provide explanations of the purpose, impact, and technical justification for each design change.
- When designing to a planned operational life, consider:
  - Corrosion of connectors
  - Accelerated wear of bearings
  - Solids causing blockages in the off-gas system.
  - Water line corrosion
  - Interlock control issues
- Avoid underestimating the importance of seemingly peripheral areas (e.g., MSMs and cranes).
- Develop feed specifications as a key aspect of the design.

Construction

- Perform dye penetrant or other non-destructive examination on critical welds before and after surface finishing.
- Conduct a thorough review of the construction drawings to ensure that all necessary weld symbols are in place and correct.

Operations

- Evaluate vitrification operations to provide checks and balances to strive for precision in chemical makeup.
- The resistance to leaching will vary by glass composition and should be tested across the range of probable waste composition to achieve the desired leach resistance. Metal oxides have varying maximum solubility levels in glass (i.e., chromium at 5%, lead at 30%), which generally far exceed normal contamination levels. If organic content of feed is over 20%, the equipment system may need to be modified depending on allowable residual organics in the exhaust and the glass.
- Select materials for melter construction based on compatibility with wastes. The mass and size of feed particles is limited by their impact on the impeller.
- Ensure that the glass is chemically and operationally compatible with the melter—glass properties should be measured and controlled for the following:
  - Viscosity at operating temperatures (necessary for efficient glass-making and to keep glass from plugging the pour spout). The 1100^{o}C operating temperature requires a careful glass formulation, which requires substantial experience.
  - Liquidus of glass (necessary to avoid plugging and accumulation of materials in melter; liquidus is the lowest temperature at which the glass will not break down and form crystals).
- If the feedstock has large amounts of inorganic salts, especially sulfates, chlorides or fluorides (essentially above 0.1 percent by weight of any of these on the dry weight basis), corrosion testing should be conducted for one month or longer to make certain that the salts will not deteriorate the electrodes. Nitrates do not seem to cause any problem, but sulfates and halides should be considered with caution.
  - With respect to electrical conductivity, resistance must be in a range where sufficient power can be generated (this has not been a significant issue, but needs to be checked).
  - Redox (oxidation-reduction potential); the Inconel is most resistant to corrosion and oxidation when it is in an oxidizing, air or weakly reducing environment. Free carbon in the glass might cause problems.
- Define and operate within the process envelope of the overall system.
- Quality assurance of vitrified product depends on quality control of feed materials and good control of the process. No active glass sampling or destructive testing is necessary; however, some US melters need to sample the glass for quality assurance purposes.
- Management of the people involved is as important as management of the technology.

Several other common operations, process control, and layup deficiencies were identified:

- Inadequate development and detail in operating procedures, both for normal operating conditions, shut-down, and emergency action
- Inadequate quality assurance on support systems, including analytical chemistry and cooling water
- Inadequate process control program development and implementation, particularly as it relates to feed material specifications
- Excessive turnaround time for process control sampling and analysis
- Incomplete integration of controls to mitigate hazards identified in analysis/reviews with all phases of operation, shut-down, standby, and cool-down procedures
- Incomplete translation and interpretation of scale-up conditions from pilot scale operational performance to production melter performance. This has required extensive and frequent down time for system and component modifications, which also results in more thermal cycles.

Decontamination, Dismantlement, and Decommissioning

Based on the initial review of melter facility experience within DOE, U.S. industry, and internationally, there is insufficient information to adequately evaluate this area. Significant experience does exist with decontamination and decommissioning (D&D) of DOE facilities at Idaho National Engineering Laboratory (INEL), Richland Operations Office (RL) and Savannah River Site (SRS) on comparable waste processing facilities. Worker safety during decontamination of refractory materials should be studied. This area will be examined in Phase 2 of this study.

3.2 INTERNATIONAL EXPERIENCE

With the exception of the some information supplied by British Nuclear Fuels, Limited (BNFL) for its Sellafield, England, vitrification plant, the literature reviewed to date does not address design or operational problems with vitrification systems outside the U.S. that can be incorporated in this phase. Lessons learned at Sellafield, as provided by BNFL, include the following:

- Quality of vitrified product depends on good control of feed material quality and the process. Development of feed specifications is a key aspect, and definition of, and operation within, the process envelope are crucial. No active glass sampling or destructive testing is necessary.
- Life expectancy cannot be tested during startup.
- Do not underestimate the importance of seemingly peripheral areas (e.g., support systems such as cranes and master/slave manipulators).
- All HLW nuclear thermal treatment plants are challenging to operate; there is no magic solution; expect to improve by some increment each year.
- Management of the people involved is as important as management of the technology.

Additionally, the Mixed Waste Focus Area and others are knowledgeable of work in Russia—especially the hybrid plasma/induction melter referred to as Plasma Induction Cold Crucible Melter (PICCM). France is also very experienced, and Japan may have relevant experience.

4.0 DOE LOW–LEVEL WASTE VITRIFICATION EXPERIENCE

4.1 FERNALD VITRIFICATION PILOT PLANT

System/Equipment Description

The Vitrification Pilot Plant (VITPP) System at the Fernald Environment Management Project (FEMP) was designed as a Joule-heated melter to demonstrate the feasibility of vitrifying low-level uranium processing wastes contained in the silos at the FEMP's waste storage area. The unique characteristics of these wastes require high temperature operations (1100°-1400°C range) for destroying sulfates in concentrations up to 15 weight percent combined with lead in concentrations up to 12 weight percent. This required a unique design to address the oxidation and reduction environment in the melter. Figure 4 is a block diagram of the Fernald VITPP.

The pilot plant was to be operated as a two-phase demonstration project:

- Phase 1: Process surrogate material to verify that systems and components operated as designed, establishing viable glass formulas and documenting process limitations. The performance would then be used for the full-scale plant design.
- Phase 2: Retest vitrification process using actual silo waste materials for final verification that vitrification is a viable method for waste processing.

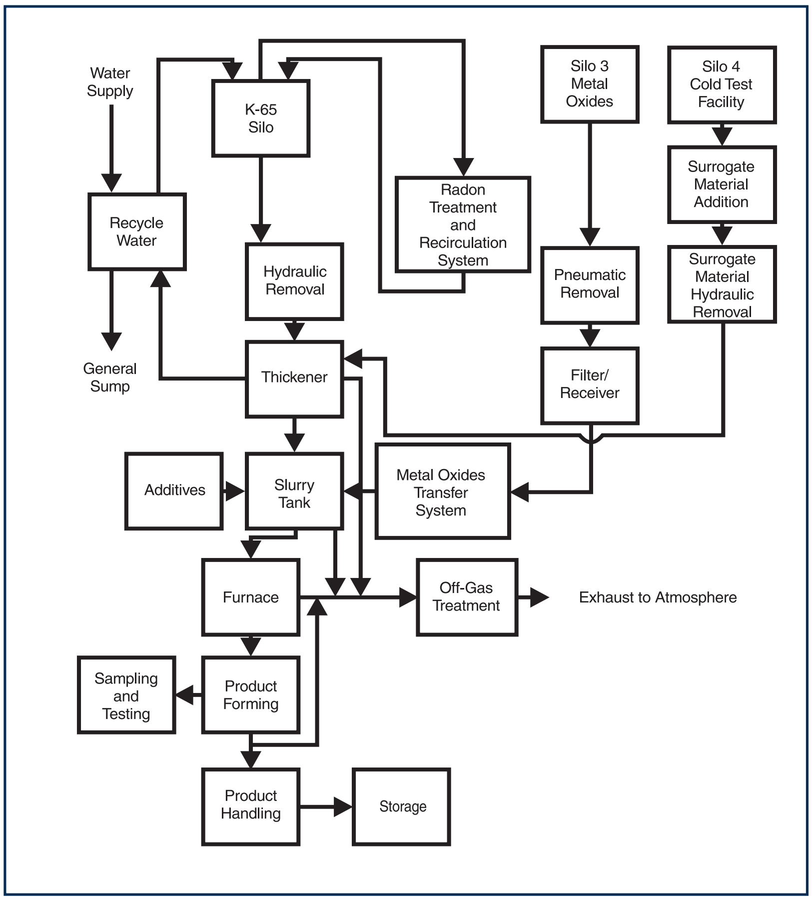


Figure 4. Process Flow Diagram of Fernald Vitrification Pilot Plant

The melter is an electric furnace (Figures 5 and 6), which provides heat through molybdenum electrodes, creating a temperature of 1400°C. The unique three-chamber melter configuration isolates the molybdenum electrodes from the central melt area by refractory brick walls. The melter area is the central 27 cubic feet chamber, which is charged with the wastes and the glass forming materials. The two side chambers are each sized to house five molybdenum electrodes, which are shielded with benign molten glass. The side chambers are separated by the refractory brick walls (E-walls) from the main chamber where the waste glass resides. The heat is dispersed from the electrode chambers through high-conductivity Monofrax E refractory brick walls that transfer heat to melt materials without transfer of corrosive waste elements to the electrodes. The molten waste glass is then lifted by the air lifter through the discharge riser. The discharge riser is located in a smaller chamber attached to the side of the melter. Five air-bubblers, four bottom drains, and an air-lift lance are provided in the center chamber. The bubblers blow compressed air into the molten mass to help mixing and improving the melt rate. Also, the air bubbles oxidize metallic components in the wastes, prevent the formation of a metallic layer under the glass pool, disrupt the formation of a top sulfate layer, and increase convection in the glass mass for improved production rates.

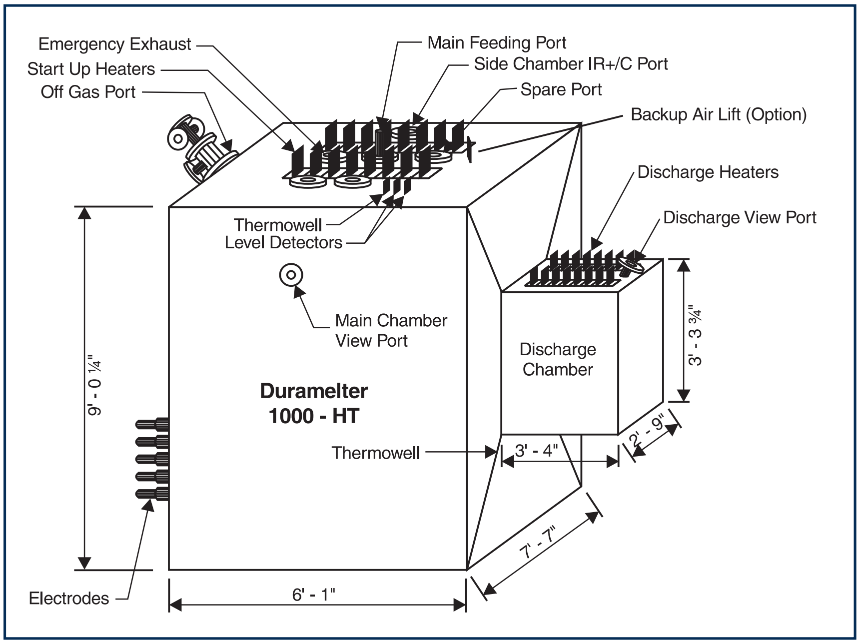


Figure 5. Fernald VITPP Melter

The air-lift lance, made of a molybdenum disilicide tube, injects air under pressure, which raises the molten glass to a level high enough above the discharge port gullet to flow out into a receiving container. Four bottom drains, two in the center chamber and one each in the electrode chambers, are provided to empty the melter.

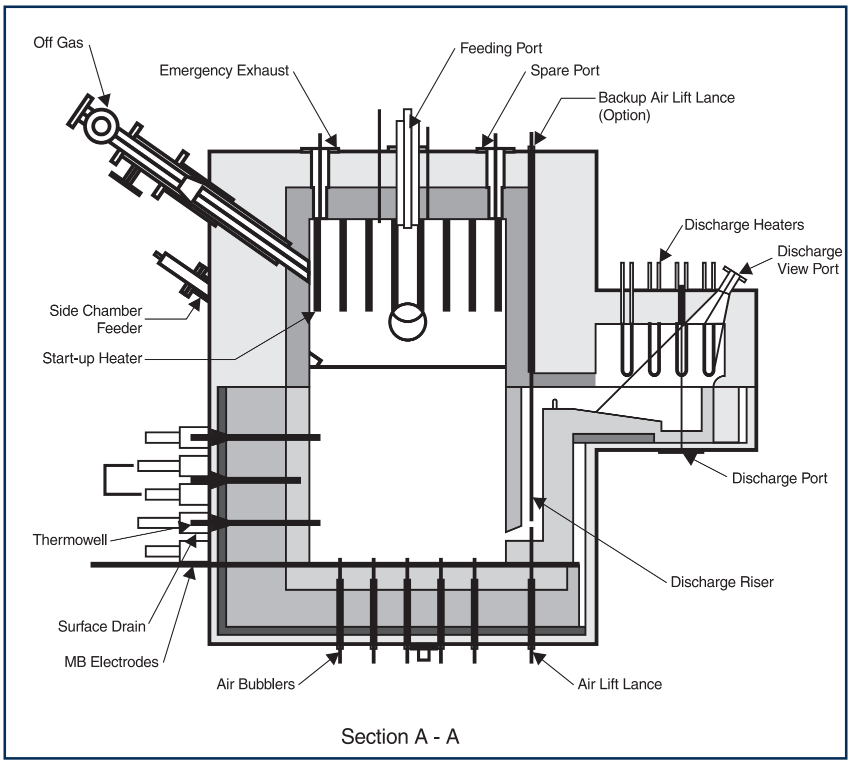


Figure 6. Cross Section of Fernald VITPP Melter

The outer melter shell is a welded steel structure that supports the electrodes and their cooling jackets, lids for the melter and discharge chambers, surface and bottom drains, bubbler tubes and various thermowells. The glass contact refractory is fused cast Monofrax K-3, which is backed by a bonded Zirmul Alumina-Zirconia-Silica (AZS) refractory and a castable aluminum oxide refractory. The glass containment refractory is enclosed in an internal Inconel 690 shell. Between the internal and external shells, a refractory ceramic fiberboard insulation is provided to prevent excessive heat loss.

Above the glass containment level in the melter, the refractory consists of Monofrax H and multiple layers of insulation from inner areas to the outer shell.

Age and Operating History

Hazard analysis, fire safety, operability and occupational safety reviews and analyses began in April 1994 and were completed in mid-March 1996. The melter bake-out began on May 18, 1996, during which the melter temperature was raised gradually to the range of 1150°-1250°C. The objective of bake-out is to cure the refractory linings through a gradual temperature increase, so the refractories are not subject to thermal shock. During the bakeout, the melter is charged with benign glass, and the molybdenum electrodes are inserted. Phase 1 of the melter testing program was subdivided into four campaigns, each designed to develop operational knowledge and experience leading up to testing with actual silo wastes, which was to be the subject of Phase 2.

The purpose of the first campaign, which started on June 22, 1996, was to synchronize the melter and the gem machine (the end-product is small glass "gems") in the temperature range of 1150°-1250°C and to increase glass production from one metric ton/day to three metric tons/day. The second campaign started on August 26, 1996. The objective was to displace the benign glass of Campaign 1, perform a 36-hour melter acceptance test, an 8-hour gem machine acceptance test, and run a Series D surrogate material (a blend of Silos 1, 2, and 3 materials), at an operating range from 1250°-1350°C. Urea was added to the slurry feed for the destruction of sulfates and to maintain glass production rates. The third campaign, which was later canceled, was intended to simulate vitrification of the high-sulfate Silo 3 wastes, to create an oxidizing environment, coupled with close monitoring of redox for controlling metallic lead production. The fourth (and final) campaign of Phase 1 began on November 29, 1996, and the goal was to simulate the chemistry of Silos 1 and 2 materials (the K-65 wastes) at lower operating temperatures.

Problems and Lessons Learned

Technical and operational problems occurred throughout the campaigns, particularly in maintaining temperature control within the melt pool. Numerous corrective measures were developed and applied with varying degrees of success. On December 26, 1996, glass breached the bottom of the melter and spilled onto the floor. The melter was shut down and has remained shut down to date, pending management decisions regarding future treatment of the silo wastes. A number of the design, construction, and operational problems specific to the melter system experienced at Fernald follows.

- During bake-out, the frit feed tube became clogged and had to be cleared by mechanical agitation.
- Two weeks after start-up, the melter began automatically discharging glass, which resulted in clogging of the discharge opening as the glass cooled. The discharge chamber temperature had to be raised to melt and flush out the accumulated glass to maintain functionality of the discharge chamber.
- One month after start-up, cracks appeared in the E-brick walls.
- To combat oxidation of the molybdenum electrodes, frit was added to the side chambers, but, as a result, the melter experienced frequent auto-discharging and the consequent clogging of the discharge opening.
- Despite installation of a discharge chute liner, and later, an Inconel shoe, cracks in the refractory around the discharge orifice continued to allow glass to migrate to the area between the refractory and the shell.
- Clogging of the discharge orifice proved to be a continuing problem throughout the test campaigns.

- Air leaks occurred between the airflow indicator and a bubbler tube, which resulted in failure of the indicator to reveal that the bubbler was actually inoperative.
- Leakage of the various cooling jackets was a recurring problem.
- Short circuits occurred between melter components and ground.
- Conditions indicated by the melter instrumentation, i.e., sensors and indicators, often did not correlate with the fault conditions that were occurring.
- High temperatures (high enough to cause the shell to glow) and stray electrical currents occurred repeatedly in the areas of the bottom drains and defied efforts at correction. These conditions continued for approximately three months until the ultimate refractory/shell failure occurred, which resulted in the spillage of three tons of glass onto the floor.

Operational events resulted in the following lessons learned.

- The bubbler tube erosion problem was documented in the Phase 1 Test Plan, Hazards and Operability Report. It was omitted in the Final Hazard Analysis Report without addressing the concerns. Proper organizational controls and protocols must be installed to formally resolve such technical safety concerns through an approval process.
- Project personnel knowledge about the facility design, construction and operation was less than adequate. The project personnel were not experienced enough to recognize the limitations of the unique melter design, special materials, and components. All such personnel should be trained by melter experts. Industry experts should be associated as consultants, and research of the publications of material suppliers should be conducted to evaluate the quality of contracted designs.
- The Invitation for Bids (IFB) failed to institute any formal controls on design changes. Contracts must specify the site requirements for change control prior to release of the IFB and/or Request for Proposal (RFP).
- The engineering, procurement, and construction processes were compromised in attempts to recover schedule slippages. Concurrent design of plant components led to uncoordinated design changes, additional schedule delays, and cost overruns. Increased design control protocol should be instituted to coordinate all design changes when more than one organization is involved in the design phases.
- Numerous design deficiencies were identified during VITPP melter operations and post-event inspection. The following recommendations should result in more efficient melter designs:
  - Consider alternate melter designs (such as gas, low-temperature, electrical)
  - Evaluate materials of construction for form, function, fit, reaction to each other, and life expectancy (e.g., molybdenum disilicide and lead, riser blocks, AZS)
  - Minimize or eliminate refractory penetrations
  - Incorporate reliable temperature monitoring of the glass pool
  - Incorporate ground current monitoring in the melter design
  - Improve reliability of melter discharge chamber
  - Improve reliability of melt-pool level indicator
  - Incorporate redundant back-up and support systems
  - Perform dye penetrant or other non-destructive examination on critical welds before and after surface finishing, particularly with cooling jackets
  - Develop performance specifications with the help of industry experts during technology selection, design phases and design reviews.

- Ensure timely analytical results of the sample product. Due to lack of timely analytical results, operational productivity was impacted, reaction to changing conditions was delayed and assessment of the effects of operational adjustments could not be determined. Reliance on three remote laboratories for test results entailed excessive turn around time for sample analysis. Advance notice to support organizations to plan for timely assistance will enhance the quality of melter operations.
- Evaluate critical components for overall effective operations. Breakdown of level indicators and thermal wells were detected during operations, and other components made of the same materials such as air lifts and bubblers were not examined for potential failures. All process materials and components should be base-lined before start-up. Operation procedures and sequences should be analyzed through failure modes and effects analysis before start-up, and casualty procedures should be developed to minimize effects of an abnormal condition or event.

4.2 SAVANNAH RIVER-VENDOR TREATMENT FACILITY

System/Equipment Description

The Vendor Treatment Facility (VTF) consists of an 8,900 kilogram per day Joule-heated refractory-lined melter with associated wastewater feed preparation, dry chemical addition, and melter off-gas treatment. The process flow diagram for this facility is shown in Figure 7. A batch system is used due to space limitations. Blended wastewater sludge is pumped into a tank where the dry chemical addition system forces dry chemicals into solution thereby creating a slurry mixture. The slurry mixture is pumped to another continuously circulated tank prior to being pumped to the melter for vitrification. The melter contains three electrodes with two phase power. The sludge to be treated is 30 percent solids, of which half is sodium nitrates. When the slurry enters the melter, the water is evaporated, the inorganic salts are calcined to metal oxides, and the resultant mixture fuses into a uniform melt, which mixes with the molten glass inventory. Air is introduced near the floor of the melting cavity to induce agitation and provide the proper redox state for the melter pool. Organic species are oxidized to carbon dioxide and water, and metals are converted to their oxides. The melter's multistage off-gas treatment system consists of a film cooler, water

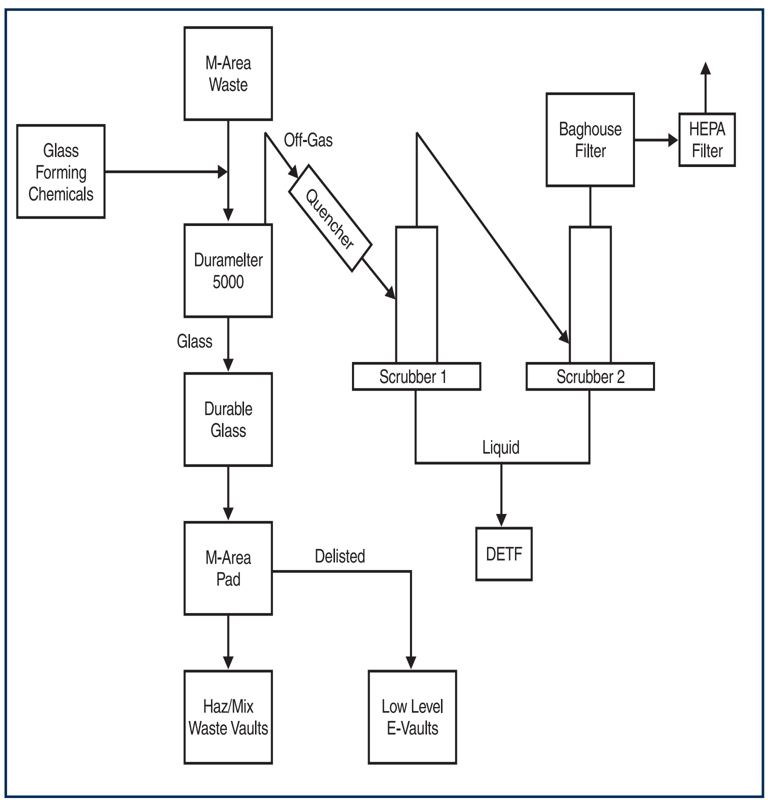


Figure 7. Savannah River Vendor Treatment Facility Process Flow Diagram

spray quencher, scrubbers, and baghouses. The melter drains are air cooled, not liquid cooled as in the Fernald melter.

Age and Operating History

GTS Duratek was awarded a $14 million fixed price contract to treat 670,000 gallons of Savannah River M-Area electroplating process sludge in the VTF. The VTF will vitrify the waste and produce highly durable glass pellets, which will be stored inside 71-gallon square drums. Duratek completed the VTF in January 1996 and began converting sludge into glass in October 1996.

Problems and Lessons Learned

At Savannah River, the GTS proprietary DuraMelter ™ refractory package is a layered series of materials typical in melter design. Molten liquid perforated these layers and leaked out on May 17, 1996, during non-radioactive startup testing. The ensuing investigation reported that the cause was anhydrous borax (a glass forming agent) being fed directly into the melter when the glass melting chamber temperature was 1000^{o} C (see Occurrence Report SR–WSRC–RMAT–1996–0003). The borax then melted, floated on the glass-pool surface, flowed into an AZS brick joint and out to the inner shell (due to the low viscosity of borax). This led to an electrical short circuit between the electrodes and the inner shell (due to the higher corrosivity and conductivity of borax). The electrical short caused localized Joule heating, which led to the refractory damage.

To prevent any kind of Joule heating between the electrodes and the inner shell, and to lower the temperature of the inner shell, the following modifications were completed to remove the insulation and add brick in the three-electrode bus region. During these modifications, heating of the melter continued with the east electrode only.

(1) The bus openings on the outer shell were enlarged.

(2) The fiber insulation between the inner and outer shells in the region close to the end of the electrodes (the area above the original inner shell cowl) were removed.

(3) The additional cowls around the original cowls were welded around the new opening on the inner shell.

(4) AZS bricks (3 in. by 5 in. by 12 in.) with hot patch material (Corhart 271-Zircon patch) were put inside the new cowls, and the top cowl cover was fully welded.

(5) New narrow bricks were added on both sides of the additional inner shell cowls between the inner and outer shells to prevent further bending of the inner shell opening.

(6) Hot patch material was used to fill all other gaps and openings in these modification regions.

Following these modifications, on June 13, 1996, there was a glass leak from a bottom drain plug, and on August 1, 1996, leakage through the inner shell was observed but there was no release through the outer shell to the environment. The investigation (see Occurrence Report SR–WSRC–RMAT–1996–0004) reported that the failures were also caused by Joule heating within the brick seams of the melter. The melter was then converted from a two-phase to a single-phase melter to reduce the voltage potentials that cause the Joule heating. Additionally, cantilever supported plugs were installed on the melter.

The root cause is a design problem—error in equipment or material selection, and the direct cause is an equipment/material problem—defective or failed part. The cause was refractory failure, and the lesson learned was to refrain from adding anhydrous borax; consider another glass forming agent.

On March 18, 1997, a hot spot was detected on the melter at the northern region of the melter center electrode. Compressed cooling air was directed at the hot spot to mitigate the temperature, and normal operations continued. On March 25, 1997, another hot spot was detected in the eastern region of the melter center electrode. Sludge feeding was suspended, the hot spot cooled, and sludge feeding resumed. Prior to restart, Engineering specified power limit settings of 250 kW on the east and west electrodes to minimize the potential of discharging glass through the bottom of the melter due to uncontrolled Joule heating. Acceptable melter operation was achieved and maintained until March 27, 1997, when a hot spot was detected at the northern region of the center electrode (same location as the hot spot on March 18, 1997). This time, air was not effective in cooling the hot spot, and GTS Duratek Corporate Headquarters shut down VTF operations (see Occurrence Report SR–WSRC–RMAT–1997–0004). Operations were restarted on December 12, 1997 and was completed in February 1999. The original melter was replaced with an improved melter design.

GTS Duratek has verbally advised that it is analyzing the failure, has a replacement plan, and is preparing a lessons-learned report. Due to the proprietary nature of these documents, they can not be included in this report. DOE should request lessons-learned information from Duratek.

4.3 OAK RIDGE TRANSPORTABLE VITRIFICATION SYSTEM

System/Equipment Description

The Transportable Vitrification System (TVS) is a large scale, fully integrated pilot plant for the demonstration of treatment of low-level mixed waste in the form of sludges, soils, incinerator ash, and other waste streams. The unit is unique because it is designed to be disassembled, transported, and easily decontaminated. Equipment is housed in modules that can be sealed for road transport. Modules include feed preparation, melter, off-gas, and control systems.

The melter is constructed of refractory blocks and superstructure and is divided into three chambers. The largest is the main (central) processing chamber, which contains the primary electrodes. Glass temperature in the melter is measured in the center of the main melter chamber by a molybdenum sheathed thermocouple. The melter is capable of generating glass temperatures between 1000^{o} and 1400^{o}C.

Slurried or dry feed is introduced into the feed preparation module where it is mixed with glass former. A slurry system then pumps the waste/additive mixture to the main chamber of the melter where it forms a cold cap on the surface of the molten glass. The cold cap helps reduce heat loss and emissions of volatile metals. Convective currents in the glass pool draw fresh, unmelted material from the cold cap into the glass pool where the vitrification process takes place. Glass is drawn through a refractory-lined throat into the second chamber. In the second chamber, a nuclear level gauge allows the operator to determine glass level in the melter and control it by moving the spindle of a submerged drain valve. Continuous glass production rates of 50 to 150 kilograms per hour can be maintained. The third chamber, which has a separate drain mechanism, is designed to remove salts/sulfates that may collect on the glass pool surface. The processing of some waste streams may result in the accumulation of metals in the main melter chamber; therefore, a third drain is provided for this possibility.

Off-gas from the melter is drawn through a refractory-lined duct to the emission control module. The off-gas system consists of a quencher, packed bed cooler, variable throat venturi scrubber, mist eliminator, reheater, high efficiency particulate filters, and fans. Treated off-gas is released through a 15-meter stack with provisions for EPA–approved particulate gas sampling.

Age and Operating History

TVS was built by Envitco. Construction of the TVS was completed in July 1995 in Erwin, Tenn. The TVS was then disassembled and transported to Clemson, South Carolina, where it was reassembled for surrogate testing by Westinghouse Savannah River Company (WSRC) and Clemson University. The TVS was operated and modified at Clemson from December 1995 through early March 1996. In late May 1996, the unit was disassembled and loaded onto 13 tractor trailers for shipment to Oak Ridge.

Lockheed Martin Energy Systems assumed responsibility for the TVS reassembly, which was completed in September 1996. The TVS was restarted in September 1996 for shakedown and surrogate testing and operated until early November 1996. On November 5, 1996, a glass leak occurred at a vertical joint between ceramic refractory blocks in the glass-melting chamber.

The primary cause of the glass leak was movement of the inclined refractory blocks forming the sloped floor of the main melter chamber. This movement allowed a gap to form at the outer joint between bottom refractory blocks, adjacent to the salt drain on the side of the melter. The gap between the blocks opened to a width of about 0.4-inch at their outer perimeter. The outer bottom refractory joints may have become progressively wider during the prior three melter heat up and cold shutdown campaigns. During the last operating campaign at the K-25 site, surrogate glass (with a relatively low melting temperature) likely entered the open joints, moving outward. As the refractories became hotter, glass likely penetrated further into the open joint. Of the three drains on the melter, the only one used to date is that on the main melter.

The melter leak has been repaired, and a radioactive waste melt demonstration was completed in October 1997.

Problems and Lessons Learned

On November 5, 1996, approximately one ton of glass leaked from the melter and flowed between the steel floor and subfloor of the melter module, burning cooling hoses, power cables, and instrument wiring routed between the floor and subfloor. Glass did not escape the melter module building, and there were no personnel injuries. The cause of the glass leak was determined to be the result of a combination of design factors and operating conditions that prevented the maintenance of adequate compression of the refractory joints when the melter was thermally cycled through heat-up and cool-down cycles. A team was formed to investigate the causes of the glass leak and to review the investigation findings.

Both the refractory configuration and inadequate adjustment of the melter binding steel during cooldown were likely factors contributing to the opening of the bottom refractory vertical joints to the extent that a glass leak was initiated. The increased operational temperature required when melting the clear glass cullet to flush the melter was also a contributing factor—in that it probably helped soften the lower-melting glass that had already seeped into the refractory joints during earlier operational tests on surrogates, both at Clemson and at K-25.

The inclined bottom refractory blocks are supported by wedge-shaped refractory blocks that appear to have been forced outward as a result of the downward forces of supporting the melter sidewalls, the inclined bottom refractory, and glass inventory. This movement allowed the outer perimeter of the inclined bottom refractory blocks to settle, thereby causing the vertical joints between these blocks to open. The vertical refractory joints in the TVS were held in compression by hoop stress retaining forces provided by binding bolts connecting the outer cooling panels. To maintain appropriate compression of the glass contact refractories, the Envitco manual specified that these binding bolts should be loosened as refractories expand, when the melter is heated, and that these bolts should be tightened as the melter cools.

It is not clear whether proper binding steel bolt adjustments were made during each heat-up and cool-down cycle of the TVS to maintain the required compression of glass contact refractory joints, or whether the existing design and procedures were adequate to maintain refractory joint compression during thermal cycling of the melter. Glass melt temperature was maintained at about 1360^{o}C for several hours prior to the leak. Analysis of the leaked glass samples indicated a melt viscosity of approximately 80 poise at 1360^{o}C, which is near the upper end of the target melt viscosity range of 20 to 100 poise for TVS operation.

Operational events resulted in the following lessons learned and are documented in the project's lessons learned.

- Both the glass leak incident and the appearance of solidified and devitrified glass in open refractory joints of the TVS served to highlight the importance of proper binding adjustment during thermal cycling of the melter to maintain compression of refractory joints. Modification of the refractory binding system and revisions to procedures are warranted, especially if the melter is to be rebuilt with longer life, high-performance refractory materials.
- Operations should be planned to minimize thermal cycling. Research data has shown that for thermal cycling considerations, idling the melter in a hot standby mode for periods up to a few months would be preferable to cold shutdown. This would also minimize the requirement of flushing the melter with higher melting temperature SLS glass prior to cold shutdown at the end of each vitrification campaign.
- The probability of a future glass leak may be reduced by design revisions expected to be incorporated as part of the TVS repairs and by maintaining proper adjustment of the refractory binding steel bolts during operation. Achieving a zero probability of future leaks or spills is likely not realistic or practical.
- The routing of hoses, cables, and instrumentation wiring between the floor and subfloor made them vulnerable to burning and destruction as a result of a glass leak. Smoke from burning hoses and cables was also a hazard to personnel entering the melter module to stop or mitigate the leak. Design modifications to re-route hoses, cables, and instrument wiring clear of potential glass flow during a leak event should be part of the melter repair activities.
- Vitrification processing and melter operation are technical activities requiring skilled and experienced operations personnel. Operations oversight by qualified engineers is important. Operator training and qualifications should be reviewed and certification criteria established prior to initiation of future production operations based on experience gained during the demonstration operations.
- Emergency response procedures have been prepared for TVS operations. Development of a "pre-fire plan" has been recommended and should provide a basis for an additional TVS emergency response procedure. Emergency response procedures should be reviewed and emphasized during training of TVS operations personnel.
- The Lexan guarding installed for the purpose of preventing accidental personnel contact with powered electrodes and exposed power connectors also inhibited observation of exposed refractory joints and adjustment of melter binding steel bolts. The guarding panels could also interfere with the use of water lances to stop a glass leak. The guarding should be redesigned to avoid interference with access to the melter for such purposes.

4.4 HANFORD LOW-LEVEL VITRIFICATION PROJECT

Background

The Hanford Site presents the largest LLW and HLW vitrification challenges in the DOE complex. Approximately 55 million gallons of defense nuclear waste are stored in 177 underground tanks on the Hanford Site. The baseline plan for Hanford TWRS is to retrieve this waste, and through pretreatment, separate the waste into HLW and LLW streams for treatment. When vitrified, approximately 90 percent of the total product volume would be produced from the LLW stream for disposal of on-site.

The expected composition of the TWRS LLW is primarily a caustic sodium nitrate/ nitrite mixture containing other lesser components such as aluminum hydroxide that solubilize during the caustic in-tank washing process. The washing process will be used to initially separate the LLW stream for pretreatment. Although the TWRS LLW stream contains some minor components such as phosphate and sulfate that have very limited solubility in silicate glasses, the TWRS LLW does not contain significant levels of problem metals such as lead, noble metals, or other components that present problems for vitrification processing of other DOE LLW or LLMWs.

Hanford TWRS LLW vitrification demonstration activities were mostly initiated following negotiation of the fourth amendment to the Tri-Party Agreement (TPA) which changed the treatment method for the TWRS LLW stream from grout to vitrification in late 1993 (ref W1). However, a LLW vitrification demonstration test was conducted in June 1993 with the Vortec Corporation cyclone combustion melter prior to completion of renegotiation of the TPA. Under the renegotiated TPA, construction of the Hanford Waste Vitrification Plant for HLW was canceled, and vitrification of LLW was specified in the TPA to begin before HLW vitrification. Two early TPA milestones were to begin LLW melter testing with simulants (September 1994) and to select reference LLW melter technologies (June 1996).

In response to these two TPA milestones, a two-phase program to test and demonstrate commercially available technologies for TWRS LLW vitrification was initiated, and Phase 1 testing was completed in June 1995. In September 1995, the DOE decided to privatize Hanford TWRS waste treatment, thus allowing completion of only Phase 1 of the LLW Vendor Testing Program.

Hanford LLW Melter Vendor Testing

An RFP for demonstration of technologies for vitrification of Hanford TWRS LLW was issued in February 1994. In May 1994, a source Evaluation Board selected 7 vendors for contract award from 16 proposals. The vendors and technologies selected for Phase 1 demonstration testing were the following:

- *Babcock & Wilcox (B&W),* Alliance Research Center, Alliance, Ohio, demonstrating a cyclone combustion melter using slurry feed
- *Envitco,* Toledo, Ohio, demonstrating a high-temperature Joule-heated melter with molybdenum rod electrodes using both dry and slurry feeds
- *Duratek,* Columbia, Maryland, demonstrating a low-temperature Joule-heated melter using Inconel plate electrodes and slurry feed
- *Penberthy Electromelt International, Inc,* Seattle, Washington, demonstrating a high-temperature Joule-heated melter using molybdenum rod electrodes and a moist "mix-in-the-charger" feed system
- *U.S. Bureau of Mines (USBM),* Albany Research Center, Albany, Oregon, demonstrating a carbon electrode arc melter using prereacted dry feed

- *Vectra Technologies Inc.*, Richland, Washington, demonstrating a high-temperature Joule-heated cold wall skull melter using top-entry molybdenum rod electrodes and calcined, dried, and slurry feeds
- *Westinghouse Science and Technology Center,* Pittsburgh, Pennsylvania, demonstrating a plasma torch-fired cupola furnace using slurry feed

A negotiated test plan scope for each technology was performed on cost-plus-fixed-fee contracts by each vendor using LLW surrogate provided by the DOE. A detailed summary of the Phase 1 testing, test results, and evaluation is provided in reference W3. An Evaluation Board supported by an Advisory Panel of experts was assembled to evaluate the melter system technologies and test results. The Evaluation Board concluded that the Phase 1 testing activities provided sufficient information to support evaluation of the technologies and provided a majority of the technical information required to support the TPA milestone for LLW melter technology selection by June 1996.

The Joule-heated technologies were most highly rated, primarily based on the maturity of the technology and superior melter materials balance results (low volatility and entrainment losses). Of the four Joule-heated melter systems, those of Envitco and Duratek were most highly rated. The Penberthy Electromelt melter, although similar in some design features to the Envitco melter, and with an innovative “mix-in-the-charger” moist feed injection system, failed to complete Phase 1 testing due to failure of the glass drain system. The Vectra Joule-heated skull melter, which was contained in a refractory-lined, water-cooled vessel, performed well but was rated lower than the Envitco and Duratek systems due partially to concerns over control of its bottom drain in a larger scale system and limited experience with some of the Vectra melter design features.

The Evaluation Board rated the carbon electrode melter, demonstrated by the USBM, as the next highest and judged to show sufficient promise to warrant additional evaluation as a candidate technology for TWRS LLW vitrification. The basic carbon arc melter technology demonstrated is a mature technology with an established history of commercial application in the metals and refractories industries. Excessive volatility and entrainment losses were a problem during initial USBM Phase 1 testing operations. However, partially submerging the tips of top entering carbon electrodes in the melt, maintaining a full cold top batch coverage, and a lowering of power and target melt rates significantly reduced volatility and entrainment losses while still achieving melt rates greater than achieved with the Joule-heated melters.

The B&W Cyclone combustion and Westinghouse plasma torch vitrification technologies were judged by the Evaluation Board as too immature to be considered as serious technology candidates within the TPA schedule for Hanford TWRS LLW vitrification. Excessive feed component volatility and entrainment results during Phase 1 testing, and the resulting recycle and process control implications, were particularly troublesome for these technologies.

The lowest melter volatility and entrainment losses, and best material balance results, were achieved in the Phase 1 Envitco test with prereacted dry feed. Potentially good materials balance results may have also been achieved with the Penberthy Electromelt system had melter drain failure not caused early test termination. However, slurry feeding was recommended as the preferred feed system alternative based on the assumption that Cesium-137 removal during pretreatment would not be sufficient to allow contact maintenance of the melter and feed processing systems. The benefits of reduced feed processing complexity in a remotely operated process were judged to outweigh the potentially better melter material balance results obtainable with a cold top dry feed process.

Hanford TWRS Privatization

The Secretary of Energy approved the Hanford TWRS Privatization Initiative in September 1995, and an RFP was issued in February 1996. A key feature of the TWRS privatization strategy was to have contractor-owned-and-operated facilities built by 1-2 contractor teams that would provide TWRS waste treatment services on a competitive basis. Phase 1 contracts were awarded in September 1996 to two contractor teams, one headed by BNFL and, the other, Lockheed Martin Advanced Environmental Systems (LMAES).

The vitrification equipment vendors for these two teams respectively were Duratek and Envitco, which were the two top-rated Joule-heated melter vendors in Phase 1 of the Hanford LLW Vendor Testing Program. The LLW thermal treatment technology for the LMAES contract was initially the Molten Metal Technology, Inc., Catalytic Extraction Processing (CEP) to be supplied through a Lockheed Martin limited partnership with M4 Environmental. Use of the Molten Metals CEP technology was later dropped as LMAES baseline for LLW immobilization moved in favor of Joule-heated vitrification technology to be supplied by Envitco. In mid-1998, DOE elected to award only the BNFL team to continue with the design phase of Part B of Phase I.

Details on the melter design being developed for the TWRS Privatization contractor facilities are not available at this time, and many design details may be held as vendor proprietary in the future. Four areas where the design approach has been different in past melter designs from Duratek and Envitco are in the following areas:

(1) melter containment

(2) refractory and insulation design

(3) electrodes and temperature capability

(4) the glass pouring system.

Duratek melter designs have in the past drawn on melter design experience from the WVDP. Previous Duratek melters have been contained in sealed metal (usually steel) outer jackets and have also had an inner Inconel metal shell between the glass contact refractories and the outer shell. Thermal insulation has been placed between the inner and outer metal shells to reduce heat loss and meet melter exterior cooling requirements. The inner Inconel shell also provides an internal barrier to leakage of glass. However, because the Inconel shell runs hot, there is increased potential for electrical shorting within the melter if glass or molten metal penetrates to the Inconel shell. The M-Area melter at Savannah River does not contain an inner inconel shell.

Most Duratek melters, with the exception of the VITPP melter, have used Inconel plate electrodes that limit melter temperature to less than 1200^{o}C. Duratek typically uses an “air lift” overflow drain from which glass pouring occurs when air is bubbled from the bottom of a vertical riser which causes the glass to rise with the bubbles and overflow to the pour stream. Duratek melters with full metal shell containment and Inconel plate electrodes are similar in design features to Joule-heated melters demonstrated at Pacific Northwest National Laboratory (PNNL) and used elsewhere in the DOE complex at Savannah River and West Valley, New York.

Envitco melter designs are more typical in design features to larger melters used in the commercial glass industry. Envitco melters are not contained in a full metal containment shell. Refractory blocks in Envitco designs are backed by water-cooled panels and may use insulating or castable refractory layers between the glass contact refractories and the exterior water-cooled panels. The melter assembly is held together by bolts connecting the cooling panels and by jack bolts from external steel frame structures.

Envitco designs typically use minimal thermal insulation between the glass contact refractories and exterior cooling panels. Increased refractory life is a claimed advantage for using minimal thermal insulation and running the back side of glass contact refractories cooler. Envitco melters use molybdenum rod electrodes and electrode holder designs derived from commercial glass industry designs that allow glass melting temperatures up to 1500°C when using high temperature refractory materials. Envitco has used proprietary mechanically operated drain valves to control glass pouring in past designs. It is uncertain at this time if multiple mechanical drain valves of this type, or some other design such as an overflow weir, were to be used in the Hanford TWRS LLW melter design.

Problems and Lessons Learned

The lessons learned from deficiencies in the small scale testing for Hanford are considered insignificant for this report.

5.0 COMPARABLE EXPERIENCE WITH HIGH LEVEL WASTE VITRIFICATION FACILITIES

5.1 SAVANNAH RIVER—DEFENSE WASTE PROCESSING FACILITY

System/Equipment Description

The DWPF is located at the SRS near Aiken, South Carolina. Its purpose is to immobilize existing and future high level liquid radioactive waste. Approximately 34 million gallons of waste containing 480 million curies are presently stored in large underground tanks. The wastes are by products from the processing of nuclear materials for national defense, research, and medical programs.

DWPF is composed primarily of the vitrification facility, Glass Waste Storage Building, Fan House, pump pit, waste water treatment facility, and several other support buildings. Washed sludge from both the Extended Sludge Processing (ESP) and In-Tank Precipitation (ITP) facilities are fed into the vitrification facility to produce a vitrified, leach-resistant glass product that can be enclosed in welded, leak-tight stainless steel containers. The Vitrification Building houses a Joule-heated glass melter and all associated equipment required to vitrify the high-level radioactive waste. The process flow diagram for the vitrification facility is shown in Figure 8.

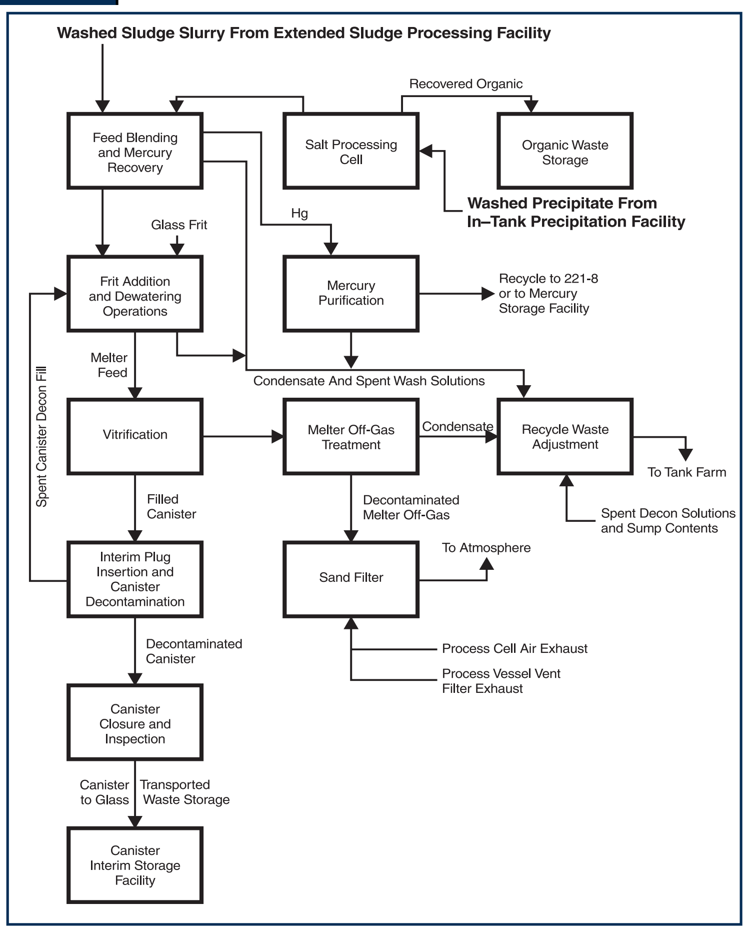


Figure 8. DWPF Process Flow Diagram

The Vitrification Building receives washed sludge and precipitate (process feed) processed in the chemical and salt processing cells to form a slurry, which is fed into the melter. The melter is operated continuously with a crust (cold cap) composed of waste calcine and frit that covers most of the melt surface. The feed slurry is introduced onto the top of the cold cap. Water from the waste slurry is evaporated and drawn into the off-gas system (Figure 9). The glass melt beneath the cold cap is at a temperature of 1050^o to 1170^{o}C, which causes the cold cap to melt from the bottom and form a borosilicate glass waste matrix. The melter uses Inconel™ 690 electrodes in the refractory lined chamber.

Following melting, the glass homogenizes in an average residence time of about 60 hours before it is poured. After mixing, the molten glass flows through the melter throat, up the riser, and down the pour spout into a stainless steel canister connected to the melter by a bellows. The canisters are 10 feet high by 2 feet in diameter and contain 4,300 pounds of glass. Filled, sealed, and decontaminated glass waste canisters are delivered to the Glass Waste Storage Building for storage. The melter off-gas process includes two parallel systems of equipment designated as the primary and the backup.

Age and Operating History

Development of the DWPF melter and associated processes began in the late 1970s, and over 1,000,000 pounds of glass was poured by research melters. Congress authorized the DWPF as a 1981 project. Cold chemical runs were started in October 1992, the melter began operations in June 1994, and radioactive operations began in March 1996. As of January 21, 1999, a cumulative total of 555 canisters have been poured.

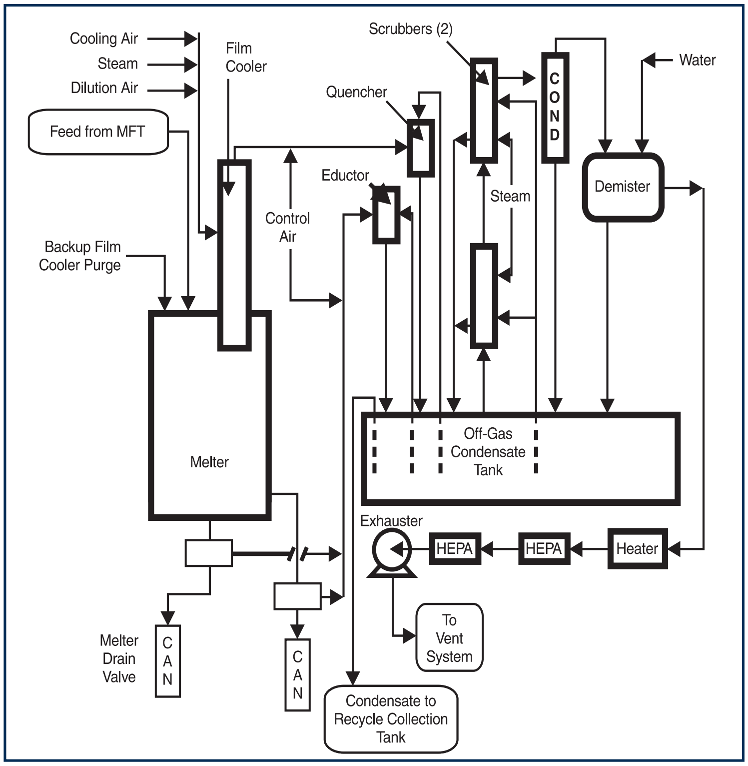


Figure 9. DWPF Melter Off-gas Process Flow Diagram

Problems and Lessons Learned

On April 3, 1993, the DWPF Melter was inadvertently flooded during the restoration from Off-Gas System startup testing during cold chemical runs, and a DOE Type B investigation board was appointed. During the performance of the restoration, an unplanned excessive vacuum was drawn on the Melter, which resulted in the movement of water from the seal pot to the Melter.

The Investigation Board concluded that the necessary programs required to support a successful transition from the construction phase to the operating phase were not effectively implemented. The lesson learned from this event was that system design must provide adequate vacuum protection for systems or components when positive displacement pumps or blowers are used. Positive displacement pumps may cause pressure spikes, and vacuum protection can prevent migration of materials during leaks. Operator action or administrative controls cannot be relied on to mitigate occurrences that can happen faster than the operator's ability to respond. After glass pouring operations began, problems developed with the stability of the glass pour stream, which caused the stream to wick and migrate from the intended release point of the glass at the upper knife edge of the pour spout. This wicking produces an accumulation of glass in the lower pour spout and bellows area that has required significant time and effort to clean. Later investigations determined that the wicking problem was caused by erosion of the knife edge and not differential pressure variations as suspected earlier. Variations in composition or pour spout temperature and deposits in the pour spout cause changes in the physical properties of the pouring glass and are also likely contributors that should be minimized.

Weld corrosion of melter cooling water system piping, due to microbiologically induced corrosion (MIC), caused selected 304L stainless steel piping system weldments to exhibit exterior evidence of corrosion (SR–WSRC–WVIT–1991–1004). The melter cooling water system was hydrotested, flushed, and tested using neutralized well water because the National Pollutant Discharge Elimination System (NPDES) outfall permit did not allow water containing biocide or corrosion inhibitor to be discharged. The lesson learned is to include recent and complete information on environmentally induced problems such as MIC in the basic design report and the safety analysis report. Include and follow design specifications for water quality.

5.2 WEST VALLEY DEMONSTRATION PROJECT – VITRIFICATION FACILITY

System/Equipment Description

The WVDP is located 30 miles south of Buffalo, New York. Originally built and operated as a plutonium uranium extraction (PUREX)-based reprocessing plant for commercial nuclear fuel, the site was shut down in 1972, then turned over to the State of New York in 1976. As a result of the reprocessing operations, the site was left with 2,200 cubic meters (600,000 gallons) of high-level liquid radioactive waste. This Waste was neutralized with sodium hydroxide and stored in an underground carbon steel tank. A sludge layer of insoluble hydroxide, mostly ferric hydroxide, precipitated to the bottom of the tank, leaving a relatively clear supernatant above the sludge in a ratio of approximately 1 gallon of sludge for every 11 gallons of supernatant.

The primary radioactive isotope that remained in the supernatant was Cs-137. The other radioactive isotopes, mostly strontium (Sr-90), became part of the sludge. The supernatant contained 16 x 10^6 curies (Ci) of activity, and the sludge contained an additional 16 x 10^6 Ci. There are four HLW storage tanks at the WVDP. Carbon steel Tank 8D-2 contains the PUREX waste, with 8D-1 as a spare. Stainless steel Tank 8D-4 contains acidic thorium extraction (THOREX) waste, with 8D-3 as its spare. All of these HLW storage tanks are located in the Waste Tank Farm. Congress passed the WVDP Act to demonstrate solidification and preparation of high-level radioactive waste for permanent disposal. DOE assumed control of the site under the Act in 1982.

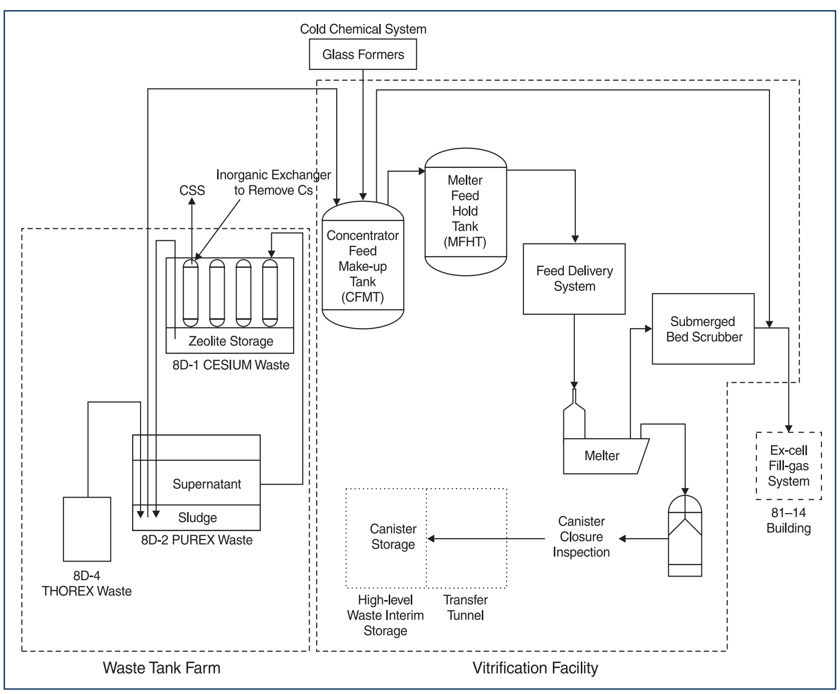


Figure 10. West Valley Demonstration Project HLW Processing Flow Diagram

The WVDP waste has been processed in two stages (Figure 10). A pre-vitrification process decontaminated much of the original liquid volume by removing the high activity (primarily cesium) with zeolite. The resultant low-level liquids were solidified in a cement matrix and are being temporarily stored as low-level radioactive waste. Final disposition of this low-level cement waste will be determined by the Environmental Impact Statement (EIS) process currently being performed for the WVDP. The remaining sludge, and the cesium-loaded zeolite, are the subject of the current vitrification campaign. In this Project, the high-level waste sludge and ground zeolite slurry are removed from the underground storage tanks and transferred to the Concentrator Feed Makeup Tank (CFMT).

In the CFMT, the high-level waste is concentrated by boiling, mixed with glass-forming chemicals, and sampled to ensure attainment of the target composition. After the composition constraints have been satisfied, the resulting slurry is transferred to the Melter Feed Hold Tank (MFHT) from which it is metered to the melter. The melter (Figures 11, and 12, and Table 3) is a 52-ton, Inconel™ 690, refractory-lined chamber, in which the MFHT slurry is fed through a nozzle located at the top of the melter.

Alternating electric current, passed between electrodes in contact with the glass, maintains the melter at 1150°C and converts the waste slurry to a durable borosilicate glass. The molten glass product is airlifted over a dam into a heated discharge cavity where it is poured into stainless steel canisters located on a turntable beneath the melter. The canisters contain 4,000 to 4,600 pounds of waste glass and are placed in an interim storage facility on site following cooling, closure, and decontamination stages. Gases generated as a result of the melting process are routed through a submerged bed scrubber located adjacent to the melter to condense the water vapor and remove most of the particulate. Additional particulate removal and NO_x destruction stages are performed prior to release of the off-gas to the plant stack.

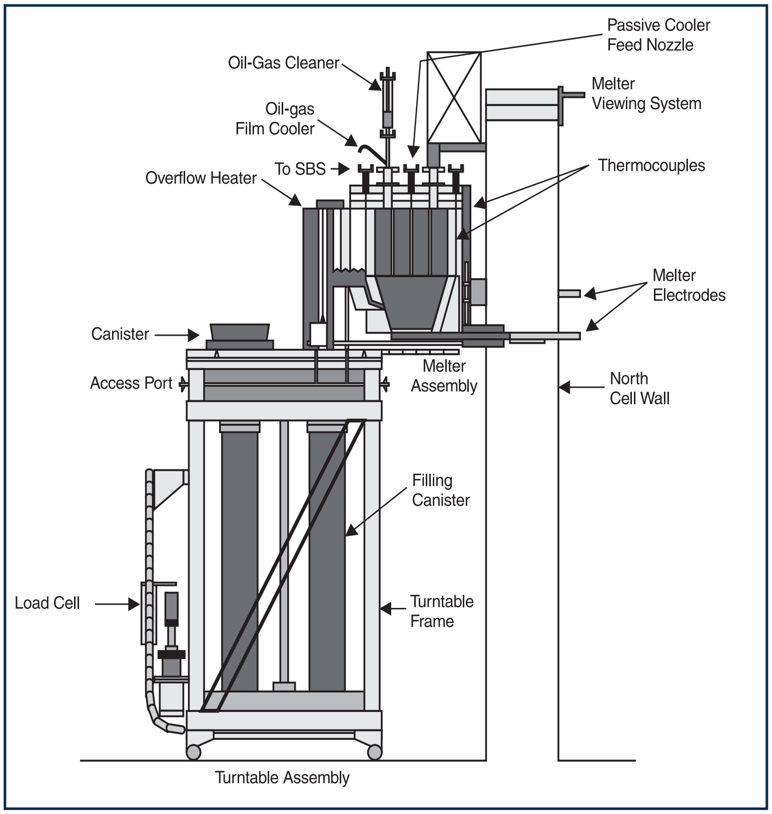


Figure 11. West Valley Demonstration Project Vitrification System

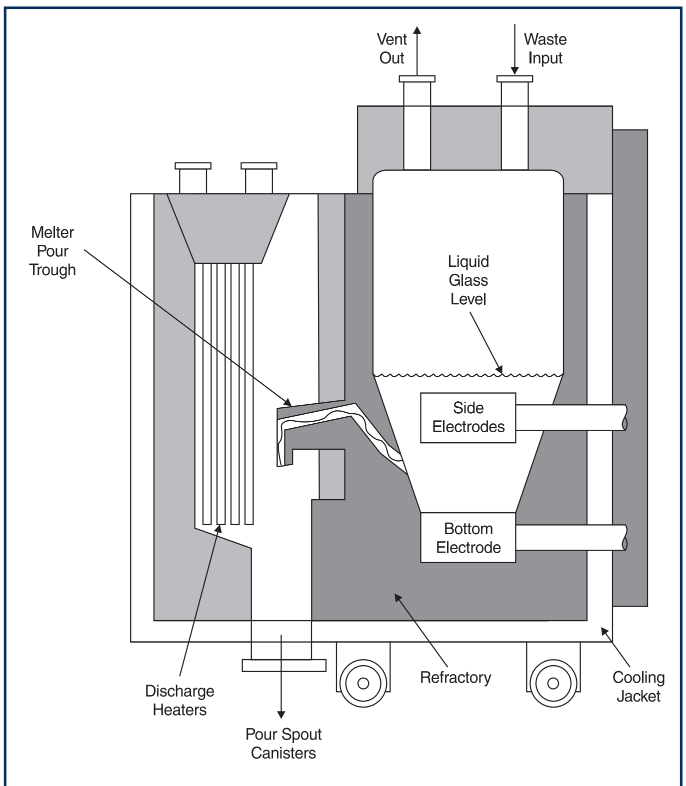


Figure 12. West Valley Demonstration Project Melter Schematic

Age and Operating History

The WVDP vitrification system was developed and demonstrated at full-scale during the five year Functional and Checkout Testing of Systems (FACTS) campaign conducted from 1984 through 1989. This program successfully produced over 200 tons of non-radioactive, simulated HLW glass (approximately

Table 3 West Valley Phase 1 Vitrification Operating Statistics & Melter Description

Waste Stream	Neutralized PUREX process HLW
External Dimensions	10′ tall x 10′ wide x 10′ long
Glass Surface Area	23.7 square feet
Refractory Materials	Monofrax H, K-3 & M; Zirmul; Alfrax 66 & B1-57; Duraboard
Electrode Material	Inconel™ 690
Electrode Geometry	Three plate electrodes located at the center of the melter floor and near the glass surface at the ends of the melting chamber
Glass Drain System	Airlift initiated overflow pouring
Nominal Operating Temperature	1150°C
Nominal Glass Production Rate	~30-50 Kg per hour
Special Features	Melter side walls and floor slope toward bottom electrode
Development Status	In high-level waste glass production
Waste Glass Production to Date	~436,546 Kg
Activity Vitrified	~9.5 e+06 Ci (^{90}Sr & ^{137}Cs)
Number of Canisters Filled	211
Canister Fill Height	90.27 %
Integrated System Radioactive Production Efficiency	~71% (12,100 feeding hours and 4,950 non-feeding hours)

one-third of the expected waste glass production) and demonstrated the production of a uniform, borosilicate glass product. The FACTS program also generated the data needed to qualify the glass and production process to the DOE Waste Acceptance Product Specifications. This operation also demonstrated the overall soundness of the melter design and provided operational data for the design of the production vitrification facility. Following completion of the FACTS program, the melter was disassembled and a post-operations examination was performed. The information gained from the examination and reviews were key inputs to the design of the WVDP production melter.

After the FACTS campaign, and prior to non-radioactive start-up tests of the vitrification facility, further pre-operational process trials were performed in a scaled down, non-radioactive "pilot plant" which included a mini-melter system. The effects of changes in the HLW composition due to the pretreatment operations were assessed using a mini-melter at the WVDP site. The primary effect of the waste treatment operations was found to be that a new waste feed reductant (sugar) addition target was needed due to the additions of sodium nitrite to the wastes as a waste tank corrosion inhibitor. The new target was developed in the mini-melter system and later verified during the final cold operations phase prior to radioactive operations.

Heat-up and non-radioactive testing of the production melter was initiated in May 1996. This was followed by six integrated operations melter campaigns designed to ensure the correct operation of the integrated vitrification system components, verify the revised glass redox control strategy, and enable a thorough evaluation of the new plant during the DOE Operational Readiness Review process.

Radioactive operations were initiated on June 24, 1996, with the first transfer of waste from the Tank Farm to the CFMT. The first phase was designated as “Phase 1” and comprised processing approximately 85 percent of the HLW contained in Tank 8D-2. Phase 1 operations were successfully completed on June 10, 1998. During these operations, 211 canisters were filled and about 9.5 million Ci of ^{90}Sr and ^{137}Cs (over eighty five percent of the HLW contained in Tank 8D-2) were immobilized. The vitrification campaign has also achieved a vitrification system availability (defined as the percentage of the total time that waste slurry is metered to the melter) of approximately 71 percent.

Problems and Lessons Learned

As shown in Table 3, the WVDP vitrification system has operated at an availability (actual time processing HLW slurry through the melter in a 24-hour-a-day, seven-day-a-week operation) of greater than 71 percent during Phase 1 Vitrification Processing. This availability rate has been achieved as a result of the extensive design, testing, study, and operations performed prior to the actual radioactive operations phase of the project. This does not mean, however, that the WVDP Vitrification Facility has operated without unforeseen opportunities and challenges. Some of the lessons learned from Phase 1 processing follows.

Feed Preparation and Sampling

- Initial waste transfers from the WTF to the Vitrification Facility had a lower curie content than anticipated (i.e., less than 100,000 Ci $^{90}Sr/^{137}Cs$ per batch). An additional sludge mobilization pump was installed into an existing HLW tank riser in a low-flow area within the tank where solids were apparently mounding. Careful management of the HLW tank level also increased batch curie inventory. By periodically decanting the accumulated liquid, the solids concentration in the transfers to the Vitrification Facility was optimized while minimizing the transfer pump plugging problems associated with pumping slurries.
- Batch makeup cycle time has been reduced since the start of radioactive operations. Due to the consistency of the waste, slurry acceptance engineers now generate chemical premix recipes well in advance of the final (post waste analysis) recipe. Independent verification of recipe calculations have virtually eliminated the need for corrective (and time consuming) chemical shims. The turnaround times for chemical analysis in support of feed batch preparation have experienced dramatic improvement relative to initial estimates. Early analytical cell mockup training and the experience gained by the lab technicians have reduced the time required for the various feed batch analyses by more than 50 percent, thereby saving 66 hours on the total batch cycle time. This is significant in that if this were not the case, batch preparation would be the limiting factor in the vitrification process. As a result, the melter can be fed continuously from the MFHT.
- A wider range of glass compositions has been studied to expand the range of acceptable glass recipes. These compositions include glasses with little or no uranium and thorium, which have become more depleted from the waste as the tank empties. With a broader range of acceptable compositions, the necessity for small adjustments in the feed will virtually be eliminated.
- The vitrification cell in-line slurry sampling units were modified based upon input from plant operators to improve the ease of remote operation. Typical sampling time was reduced from eight hours to one hour.
- Preparation of HLW melter feed slurry should not be the bottleneck for continuous waste vitrification. Evaluate the integrated system design to ensure that there is sufficient feed preparation tankage redundancy and analytical chemistry cell and laboratory space to ensure continuous melter feed slurry availability.

- During November 1996, waste slurry momentarily flowed into the compressed air supply pipe for the melter feed pump outside of the vitrification cell containment during an attempt to clear a blockage in the feed slurry sampling system. This flushing evolution was performed under the direction of an engineer using an unreviewed procedure. The design contingencies incorporated into the air supply system piping prevented prolonged residence of waste slurry within this pipe. During the subsequent repair operation to replace the contaminated pipe section, three workers and a section of the operating aisle were contaminated. Significant improvements to the Radiation Protection, operating procedure compliance training, and conduct of operation program improvements have been implemented as a result of this event.

Melter Operation

- Processing experience gained during the five years of initial non-radioactive melter operational testing, combined with recipe experimentation in a scale vitrification (mini-melter) system, has been successfully applied to radioactive operation. During these tests, glass chemistry (largely oxidation-reduction) studies, and methods of chemistry control were developed and have yielded excellent correlation with radioactive operations.
- Elevated levels of airborne contamination were detected in January 1997 in an operating aisle outside of the vitrification cell. The operating staff were removed from the affected areas, and no personnel contamination was detected. The subsequent engineering assessment determined that the contamination had been transported from the melter, along the discharge heater power supply electrical conduits, by minor melter pressure spikes. These conduits carried the wiring from the ex-cell power controllers to the melter discharge heaters inside the vitrification cell. The barriers installed to seal the conduits from the ex-cell operating aisles had not been totally effective in preventing the contamination migration. To prevent pressurization of the conduits, vents were opened in the conduit walls within the hot cell. As an extra precaution, high efficiency particulate area (HEPA) filter vents were installed on the ex-cell portion of the conduits to prevent any future contamination spread. All of the electrical conduits connected to the vitrification cell were reviewed, and it was verified that no further contamination spread by this mechanism was possible. No further issues with these conduits have occurred to date.
- The first set of silicon-carbide discharge heater elements exceeded their expected life by approximately three months (12 months versus 9 months). Changes in operational strategies for the heaters and providing automatic backup power minimizes heater cycling and prolongs heater life. This modification is significant in that remote heater replacement requires idling the melter for two to three weeks. The following modifications were made when the second set of heaters were installed:
  (1) Heaters use maximum length for heating, thereby lowering the watt density/square inch of surface area (original heaters did not heat the full length of the bar in the chamber);
  (2) Heaters are closely matched within each zone; this was accomplished by selecting heaters with closely matched initial resistance;
  (3) Control was modified so that the watt density is the same on each heater;
  (4) The heaters are now supplied with standby power so that thermal cycling does not occur during power outages.

These changes in installation and day-to-day operation have resulted in lengthening the life of the discharge heaters to about two years.

- Melter pressure control has been a challenge from the start. Irregular off-gas flow characteristics attributed to the submerged bed scrubber (SBS), combined with the pulsing action of the ADS feed pump, create a dynamic environment for pressure control. The control system was modified by installing a high-speed data acquisition system with a quick-acting control valve. An adaptive gain feature was also incorporated into the control scheme. These modifications made melter pressure control more manageable; however, melter pressure still fluctuates. Melter pressure, controlled to maintain -12.7 centimeters H_2O, varies as much as 7.6 centimeters H_2O from the nominal set point. Consequently, the melter glass level is maintained at least 2.5 centimeters below the overflow level to preclude excessive dripping of glass into a canister between glass pours.
- An ability to view the glass pouring into the canister is essential, and the ability to see the entire glass stream pouring from the melter to the canister would be highly desirable.
- Maintaining a steady pour stream and clear discharge port is essential to continued glass production. During startup testing with nonradioactive glass, the WVDP melter experienced chronic blockages in the glass pour stream. The blockages were the result of a failed barrier between the melt chamber and the discharge chamber, which allowed glass migration and subsequent buildup at the bottom of the discharge chamber. The melter was repaired and placed back into service.
- Configuration control and quality assurance at all stages of design and operations are essential. During integrated cold operations, the seal weld between the melter dam and trough failed due to localized high stress during initial melter heat-up. Upon investigation, it was determined that the design drawings did not specify reinforcing gussets, due to a drawing transposition error. In addition, thermal expansion capability for the dam was inadequate. The operating procedure specified a heat-up rate based on protecting the refractory insulation covering the dam, instead of the dam itself. Based on a detailed thermal stress analysis of the dam and trough, the rate of heat-up specified in the operating procedure was too fast. The operating procedure was revised to allow for the additional time required for proper stress relief of the dam.
- Just prior to radioactive operations, excessive production and an accumulation of very thin glass fibers (angel hair) led to blockages in the glass pour stream. Prior to radioactive operations, the glass buildup was removed and a flow-reducing orifice was installed to reduce the airflow from the discharge chamber to the main melt chamber. Limiting the airflow through the discharge chamber seemed to successfully reduce angel hair production to an acceptable level. Angel hair formation, however, has not been nor will it ever be completely eliminated. Periodic accumulation of angel hair in the melter discharge port has been successfully overcome by re-balancing the discharge heater loads to maximize the temperature around the discharge port and melt the accumulated glass from the chamber.
- The plant design objective should be to create a system limited only to the glass melting rate. Supporting systems (e.g., waste treatment and melter feed preparation, off-gas treatment, overall system maintenance) should be over-designed, or sufficient redundant systems provided, to meet this objective. Insufficient planning for seemingly peripheral areas (process cranes and their decontamination and maintenance, master/slave manipulations, etc.) can easily lead to extended vitrification plant outages.

Canister Filling Operations

- The WVDP HLW canisters are required to be filled at least 80 percent full. Originally, canisters were typically filled to the 85 percent level. Through the field experience gained with the video imaging capabilities of the (ILDS) system, canisters are now normally filled approximately 90 percent full. While the ILDS-based levels are backed up by mass balance calculations, the accuracy provided by the ILDS system for determining the canister fill level has been outstanding. The final (reported) canister fill verification is performed by direct measurement of the glass level (using a measuring stick device) at the vitrification weld station. The variation between the canister fill level provided by direct measurement and that provided by the ILDS is usually within 1 percent.
- A significant lesson learned is that a large canister opening is vital to the success of the WVDP vitrification process. The glass pour stream must fall a distance of over 1.5 meters from the end of the trough before entering the canister. Lateral movement in the pour stream can (and does) occur due to melter pressure fluctuations, variations in the airlift flow rate, or effects of air in-leakage to the discharge chamber. The large canister opening (0.42 meters in diameter) has proven to be an effective design feature to accommodate pour stream deflections.

Slurry Transport and Level Indication

- Slurry transport within the vitrification cell is accomplished by either steam jet transfer or air displacement slurry (ADS) pumps. Steam jet operation has been as expected with no significant problems associated with these routine transfers. The throughput capability of the WVDP melter requires a low average slurry feed flow rate. The ADS pump has provided a low average feed rate while generating high slurry velocity and high back pressure. These characteristics have resulted in essentially no plugging problems normally encountered with slurry transport. Slurry transfer jets and the ADS pumps employed at the WVDP have been able to successfully transfer waste slurries in excess of 50 percent solids.
- Vessel level, density, and pressure indications within the vitrification cell are provided by bubbler assemblies. A control scheme that includes automatic periodic air blow-downs has maintained the bubblers in the CFMT and MFHT relatively free from plugging. Recent modifications to the automatic blow-down cycles have included a small (~100 milliliters) injection of demineralized water into the bubbler probes just prior to the air blow-down and are proving to be effective in maintaining clear bubbler lines.

Canister Handling and Remote Operations

- Canister closure (lid welding) using a pulsed gas tungsten arc process has become routine. There have been only a few canister lid welds that were just outside the normal range for weld parameters. The welds were corrected by simply re-performing the automatic weld. The ease of reworking a canister lid by rewelding has proven to be one of the major advantages of this system.
- Canister decontamination operations have also become routine. Early difficulties with tank temperature control and cooling coil pressurization were corrected with minor piping modifications and control loop tuning adjustments. The process generates significant volumes of neutralized decontamination and rinse solutions. Through careful scheduling of vitrification evolutions, decontamination and rinse solutions have been effectively managed by reintroducing them into the melter feed batch makeup process.

- Provide alternative process control stations outside of the vitrification building to enable safe process shut down should a control room evacuation be required.
- Portable video cameras were developed to augment the array of fixed camera positions within the vitrification process cell. These portable cameras have been very useful for generating highly detailed, close-up images of the cell components from the angles that are not possible from the fixed position cameras.
- The severe nature of the operations require that the main plant equipment be enclosed in heavily shielded and protected cells. It also mandates that process operation, maintenance of the process equipment, and component replacement be accomplished remotely.
- Most of the downtime associated with the WVDP vitrification campaign can be attributed to failure and repair of remotely operated equipment. Repair and replacement of the melter feed jumper resulted in nearly a two-month outage. However, considerable preplanned vitrification maintenance was rescheduled and accomplished during the unscheduled downtime. In addition, the WVDP was successful in its first attempt to perform hands-on maintenance to a vitrification cell remote component, following remote decontamination in the vitrification cell. The melter feed jumper was decontaminated to allow hands-on repair of its remotely operated piping connectors.

Process Off-Gas Operations

- One method used to help manage the vitrification cell water inventory is to raise the SBS operating temperature to maximize the amount of water vapor leaving in the off-gas stream. This moisture, combined with demineralized water injected into the off-gas stream to cool the in-service blower, led to some early difficulties in accurately monitoring NO_x and ammonia (NH_3) concentrations in the off-gas. Air dryer and chiller units were installed in the sampling lines to condense and extract the moisture prior to reaching the analyzers, increasing the system's NO_x abatement efficiency.
- Abatement efficiency was also enhanced by initially saturating the selective catalytic reduction bed with ammonia reactant during melter feed initiation. The ammonia addition rate to the bed is then gradually reduced as the melter reaches steady-state feeding.
- Permeable membrane filters have been installed before the off-gas system monitors measuring nitrogen oxides to remove water vapor. This has significantly improved their repeatability and reliability.
- Shortly following the start of radioactive operations, a significant restriction in the melter off-gas piping (between the melter and SBS) developed. The restriction was suspected to be caused by the collection of dried melter feed adhering to the inside surface of the piping. Remote radiation surveys showed that the buildup occurred at an acute (45 degree) elbow just a few feet from the melter. Design modifications incorporated to mitigate the blockage included the following:
  (1) A water flush line was installed into the melter air injection line. Water is periodically introduced into the off-gas stream to steam clean the piping.
  (2) A flow-restricting orifice was installed in the air line, thereby supplying motive force air for the melter ADS pump. Reduction in the airflow rate reduced the atomization of the melter feed as it was pulsed into the melter plenum. This made it less likely for the feed material to be swept into the off-gas piping.

In summary, the WVDP vitrification campaign has experienced success for plant availability and efficiency. The WVDP considers that the most significant contributing factors was the extraordinary amount of up-front study, planning, and engineering effort focused on the project. This fact can be especially validated in two areas:

(1) The amount of time, effort, and diligence devoted to the understanding of the actual waste form and final glass compositions enabled a complete understanding of how the glass science process chemistry would behave in a real production-oriented glass-making environment. Further, this desire for understanding led directly to a critical discovery regarding the redox behavior of the WVDP specific waste-glass composition. As a result of this discovery, an action plan was established prior to radioactive operations, and a study of the phenomenon was performed. This led to the development of operational limitations and parameters, which allow the WVDP to operate the SFCM without catastrophic damage.

(2) The experience of the WVDP FACTS program allowed complete understanding of how systems supporting vitrification would behave. This led to improvements in the actual WVDP vitrification design. As a result of this program and adaptation of the lessons learned, highly reliable and easily repaired systems have been built and are currently performing better than was originally expected.

The WVDP anticipates that the operations will continue beyond Phase 1 to complete the vitrification of the tank heels and overhead fluids created during the vitrification process. Upon completion of all vitrification and resolution of the current EIS recommendations for site closure, the WVDP will commence closure in accordance with the EIS decisions.

5.3 SELLAFIELD, UK—WASTE VITRIFICATION PLANT

System/Equipment Description

The waste vitrification process consists of a highly active (HA) liquor storage and distribution cell, two parallel vitrification lines consisting of vitrification and pouring cells, and container decontamination and monitoring/control cell. Attached to the vitrification plant is the Vitrified Product Store (VPS) with a capacity for 8,000 product containers. The process incorporates a rotary calciner through which HA liquor is fed and partially denitrated. The calciner feedstock is aqueous raffinate from spent fuel reprocessing operations, which is concentrated between 50 and 250 liters per ton total uranium (depending on the fuel type), and having a specific activity of about 60 TBq per liter. The calcine is mixed with glass frit and fed into a elliptical Inconel melter. The product is a borosilicate glass system with about 25 percent waste loading. The borosilicate glass system was selected for its durability, chemical stability, corrosiveness, and melting temperature. After approximately eight hours, the glass product is fed into the container situated beneath the melter. Following pouring, the container is allowed to cool, and a lid is welded on. Inspection and external decontamination are performed, after which the containers are moved to the VPS.

Age and Operating History

In 1983, BNFL constructed and operated a full scale inactive facility with its primary mission of developing the vitrification process for the highly active liquid waste. In addition to this program, another was implemented to create the glass composition needed to vitrify the waste. Early work on glasses led to the selection of the borosilicate system, which not only offers good waste form characteristics, but also exhibits good processing properties. As a result of these programs, the WVP was constructed at Sellafield. The WVP has been operational since July 1990 and has produced over 1,300 containers of glass. During this time, operation of the plant has demonstrated reliability in the manufacture of products within specifications, and has received good feedback on the quality and performance of the glass produced. Additional accomplishments have been very low levels of activity discharge from VPS, and the minimization of secondary wastes from the plant.

Problems and Lessons Learned

The very severe nature of this operation requires that the main plant and equipment be enclosed in heavily protected cells. It also requires remote operation, maintenance, or component replacement. When operations were just beginning, the intricacy of the system caused extended periods of downtime between production runs, thus restricting the amount of material put through the process.

Problems have included the following:

- Low reliability of the cell cranes;
- Reliability and maintenance problems with the master/slave manipulators (MSM). The latter are vital in repair, preservation, and rebuild phases; and
- Although the melters were designed to last a total of 2,000 hours, their average operational life was only 1,200 hours. Specific melter problems were as follows:
  - Corrosion of connectors,
  - Accelerated wear of bearings,
  - Water line corrosion,
  - Interlock control issues, and
  - Solids causing blockages in the off-gas system.

Lessons learned at Sellafield include the following:

- Development of feed specifications is a key aspect.
- Definition of and operation within the process envelope is crucial.
- Quality assurance of vitrified product depends on quality control of feed materials and good control of the process. No active glass sampling or destructive testing is necessary.
- Long term throughput of 400 to 425 containers per year is achievable.
- Life expectancy cannot be tested during startup. Although the melters were designed with a 2,000 hour life expectancy, the average operational life attained had been only 1,200 hours.
- Do not underestimate the importance of seemingly peripheral areas (e.g., MSMs and cranes).
- All HLW nuclear thermal treatment plants are very challenging to operate; there is no magic solution; expect to improve by some increment each year.
- Management of the people involved is as important as management of the technology.
- Borosilicate glass can incorporate a wide variety of HLW compositions; has good chemical, mechanical and thermal properties; and yields a consistent product.

The details of the deficiencies are proprietary information. However, it appears from the information provided that commonalities with DOE systems are evident and should be assessed; an agreement (e.g., memorandum of understanding) may be worked out between DOE and BNFL that will make the details available to DOE.

5.4 SAVANNAH RIVER—STIR MELTER

System/Equipment Description

SRS began its stir-melter program to provide a backup melter design for the HLW processing in the DWPF. Testing of the full size stir melter as a backup melter design was suspended in favor of the current DWPF melter design. Subsequently, the Stir Melter was placed at Clemson University to support Tank Focus Area activities, Hanford and Idaho waste programs, and to support DWPF research for improving pour spout and pour spout insert design. These activities will also provide operating experience that will yield basic data on the performance of the Stir Melter. All of the experimental work to date has been conducted using the six-inch square Stir Melter. The full size melter is scheduled for start-up in December 1998.

A stir-melter is a compact system that utilizes a dynamic stirring mechanism (propeller) to create an electric resistance in the glass melting process. This causes the toxic metal oxides to go into solution in glass and become non-leachable. Although intended primarily for inorganic wastes, organic constituents up to 20 percent or more may be oxidized in the melter. Multiple streams may be fed to the melter without premixing, as the material will be mixed in the melter. The stirring mechanism also contributes by speeding up the melting process, six to ten times higher than conventional melters of the same size because of the high shearing action and heat distribution. As a result of the shearing action, along with the uniform temperature in the stir-melting systems, the working temperatures are 30^{o}-100^{o}C below conventional glass melting furnaces, which is beneficial in lowering energy costs.

The melters can be constructed from advanced alloys or refractory ceramic materials with maximum operating temperatures of 1050^{o}C and 1600^{o}C, respectively. Alloy Stir-Melters are available with melt surface areas ranging from 0.5-20 square feet. The alloy systems offer significant advantages as they may be operated continuously or turned on and off without damage. The glass material is fully contained within the alloy liner.

The small size and Joule heating (no gas firing) in the melter minimize the off-gas treatment requirements. Ordinary off-gas treatment systems such as scrubbers and baghouse are used. In most cases, particulate from the off-gas system may be recirculated to the melter. Units with capacities up to 50 tons per day may be trailer-mounted for short term field use. The melter is designed for continuous operation but may be hot idled to accommodate the user's shift schedules or to avoid peak electric demand periods.

Age and Operating History

The stir-melters are probably the simplest melter to operate at the one-foot-square size. The melters are operated within 250^{o}C of the melting point of the metal tank and agitator, so temperature needs rigid control—some agitators were lost because of a faulty thermocouple placement. They were replaced in a few hours. The agitator is also under substantial mechanical stress, so whenever there is a scale-up or change in agitator design, high temperature creep of the metal needs to be considered.

The units are easy and quick to repair or modify using conventional metal working tools and welding. They are well suited to waste water treatment sludges and finely divided soils. The metal construction materials must be checked for corrosion in the melt, the air interface, and above the glass melt.

Problems and Lessons Learned

If the organic content of the feed is over 20 percent, the equipment system may need to be modified, depending on allowable residual organics in the exhaust and the glass. Materials for melter construction must be selected for compatibility with wastes. The mass and size of feed particles is limited by their impact on the impeller.

Lessons learned from Savannah River's stir melter experience include the following:

- The glass must be chemically and operationally compatible with the melter—glass properties should be measured and controlled for the following:
  - Viscosity at operating temperatures (necessary for efficient glass-making and to keep glass from plugging the pour spout. The 1100°C operating temperature requires a careful glass formulation, which requires substantial experience.
  - Liquidus of glass (necessary to avoid plugging and accumulation of materials in melter; liquidus is the lowest temperature at which the glass will not break down and form crystals).
  - If the feedstock has large amounts of inorganic salts, especially sulfates, chlorides or fluorides (essentially above 0.1 percent by weight of any of these on the dry weight basis), corrosion testing should be conducted for one month or longer to make certain that the salts will not deteriorate the metal. Nitrates do not seem to cause any problem, but sulfates and halides should be considered with caution.
  - With respect to electrical conductivity, resistance must be in a range where sufficient power can be generated (this has not been a significant issue, but needs to be checked).
  - Redox (oxidation-reduction potential); the Inconel is most resistant to corrosion and oxidation when it is in an oxidizing, air or weakly reducing environment. Free carbon in the glass might cause problems.

6.0 CONCLUSIONS

This report presents information in occurrence reports and other various documents and specific and generic insights from waste vitrification projects. The study shows that significant progress is being made in the development and application of melter systems for treating waste forms. It also demonstrates that the vitrification of low-level waste can be complex because of its heterogeneous and organic makeup; thus the planning and management of low-level waste vitrification projects need much of the careful consideration given to high-level waste projects.

Many other problems and issues remain in the vitrification of radioactive waste and significant lessons learned are evolving. A more detailed study is planned, as Phase 2 of this project, that incorporates root cause analyses, investigates operational safety, and broadens to encompass other waste treatment technologies and cost/benefits. A lessons learned workshop with domestic and international experts is also planned.

The following conclusions should be considered preliminary and will be amended or expanded as part of the Phase 2 study.

6.1 MELTER TECHNOLOGY

Experience with vitrification of radioactive wastes, both high and low level, has been primarily limited to Joule-heated melters. Alternative melter technologies should be evaluated for vitrification of radioactive wastes.

6.2 VENDOR ACCOUNTABILITY

Vitrification system vendors have not been held accountable for providing components and systems that will reliably perform the intended function. Future vendors should be required to bid their systems on a specific performance basis, that of producing very specific end-products at specified output rates. For example, contracts could provide that vendors receive no payment until their systems have demonstrated they can produce the desired products. Both DOE and site management contractors need disciplined project management systems and continuous monitoring to ensure that all necessary procedures and practices are implemented by the project staff.

6.3 PERSONNEL QUALIFICATIONS

Knowledge and experience of project personnel in melter design, components, and operations has proven to be less than adequate. Every vitrification project team needs to include, or consult with, vitrification experts during all phases of the project. This involvement should begin prior to technology selection and conceptual design and continue through development of standard operating procedures, start up, and testing.

6.4 THERMAL CYCLING

Thermal cycling is a major factor in melter availability and life expectancy. More rigorous controls are warranted in areas that have been primary contributors to frequent unplanned shutdowns. These include reliability of support systems and adequacy of operating procedures. Both thermal cycling and reliability should be agenda items for the Phase 2 Workshop.

6.5 CHANGE CONTROL AND COMMUNICATION

Execution of design changes without consultation with all impacted parties and/or failure to inform all impacted organizations have contributed to many of the problems encountered with vitrification systems. The importance of communication increases when more than one vendor or contractor is involved. Design changes should be minimized and communicated promptly to all affected organizations, including those who will operate the facility. In the same regard, any changes to the proposed operation or use of the facility should be promptly communicated to those responsible for design, construction, and permitting/regulatory compliance.

6.6 FORMALITY OF OPERATIONS

Procedure violations have contributed significantly to poor vitrification system availability. Formal conduct of operations programs should be implemented for all vitrification facilities.

6.7 ADDITIONAL STUDY

More detailed recommendations can be formulated by the following:

- Collect more information on vitrification experience abroad and from DOE facilities discussed in this report
- Perform root cause analysis
- Conduct a lessons-learned workshop with U.S. and international experts
- Summarize the analyses of alternatives to vitrification and the cost/benefits for each process stream

These additional activities are planned for Phase 2 of the project. A task force should be formed and the scope broadened beyond Fernald to include the interests and concerns of all DOE sites that are considering the application of vitrification technology to waste treatment.

ACRONYMS

ADS	Air Displacement Slurry
ANL-W	Argonne National Laboratory-West
$Al(OH)_3$	Aluminum Hydroxide
ARM	Air Radiation Monitors
ASME	American Society of Mechanical Engineers
AZS	Alumina-Zirconia-Silica
B&W	Babcock & Wilcox
BNFL	British Nuclear Fuels, Limited
CAM	Continuous Air Monitor
CEP	Catalytic Extraction Processing
CFMT	Concentrator Feed Makeup Tank
Cs-137	Cesium-137
D&D	Decontamination and Decommissioning
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
ESP	Extended Sludge Processing
FACTS	Functional and Checkout Testing of Systems
FEMP	Fernald Environmental Management Project
HA	Highly Active
HEPA	High Efficiency Particulate Area
HLW	High-Level Waste
IFB	Invitation for Bids
ILDs	Infrared Level Detection System
INEL	Idaho National Engineering Laboratory
ISV	In Situ Vitrification
ITP	In-Tank Precipitation
LLMW	Low-Level Mixed Waste
LLW	Low-Level Waste
LMAES	Lockheed Martin Advanced Environmental Systems
MFHT	Melter Feed Hold Tank
MIC	Microbiologically Induced Corrosion
MSM	Master/Slave Manipulator
NH_3	Ammonia Anydrous
NO_x	Nitrogen Oxides
NPDES	National Pollutant Discharge Elimination System
PACT	Plasma Arc Centrifuge Treatment
PHP	Plasma Hearth Process
PICCM	Plasma Induction Cold Crucible Melter
PNNL	Pacific Northwest National Laboratory
POHC	Principal Organic Hazardous Constituents
PUREX	Plutonium Uranium Extraction
RCRA	Resource Conservation Recovery Act
RFP	Request for Proposal
RL	Richland Operations Office

SBS	Submerged Bed Scrubber
SITE	Superfund Innovative Technology Evaluation
SLS	Selective Laser Sintering
SR-90	Strontium-90
SRTC	Savannah River Technology Center
SRS	Savannah River Site
SSMIV	Simulated Soil Matrix IV
TBq	Terobecquezrel
TCLP	Toxicity Characteristics Leaching Procedure
TDR	Thermal Destruction and Recovery
THOREX	Thorium Extraction
TNX	T and X Facility (Savannah River)
TPA	Tri-Party Agreement
TRU	Transuranic
TVS	Transportable Vitrification System
TWRS	Tank Waste Remediation Systems
UPS	Uninterruptable Power Supply
USBM	U.S. Bureau of Mines
VF	Vitrification Facility
VPS	Vitrified Product Store
VITPP	Vitrification Pilot Plant
VTF	Vendor Treatment Facility
WSRC	Westinghouse Savannah River Company
WTF	Waste Treatment Facility
WVDP	West Valley Demonstration Project
WVP	Waste Vitrification Plant

APPENDIX A: CURRENT MELTER DEVELOPMENT AND RESEARCH ACTIVITIES

Several industrial firms have developed vitrification systems, usually with application to waste treatment at Superfund and DOE sites in mind. In most cases, there have been at least some DOE or U.S. Environmental Protection Agency funding to support development and demonstration of the processes. These systems have been built and operated for varying periods of time; however, the literature searched to date does not report specific operational experience nor any design or operational problems. Fourteen of these firms' systems are discussed briefly below.

Seiler Pollution Control Systems, Inc., of Dublin, Ohio, is marketing a High Temperature Vitrification System originally developed in Switzerland. One of the company's principal goals is to produce vitrified end-products that can be used for industrial purposes. Although specific design features have not been released, Seiler has recently indicated that it is building one pilot unit with a processing capacity of 50 kilograms per hour, and the cost is in the $5 million range. The firm is also building and will operate a production unit in Freiberg, Germany, that will process waste from industrial firms on a contract basis.

Envitco, Inc., of Toledo, Ohio (recently acquired by the French company Cogema), has developed high-temperature Joule-heated melter systems for LLW, low-level mixed waste (LLMW), and hazardous waste vitrification applications. Two Envitco melter systems have been used in testing and demonstration activities at the Clemson University's DOE/Industrial Laboratory for Vitrification and have logged over 4,000 hours of pilot testing operations. The Envitco MM-005 melter at Clemson recently completed vitrification tests with actual LLMW from the Oak Ridge K-25 Site. The TVS designed and built by Envitco in collaboration with the Savannah River Technology Center, is located at the Oak Ridge K-25 Site (now East Tennessee Technology Park) for vitrification demonstration with various DOE mixed wastes. Envitco also participated in the Hanford LLW Vendor Testing Program and is teamed with LMAES to provide privatized vitrification services for treating Hanford LLW from the Tank Waste Remediation System (TWRS).

PEAT, Inc., of Huntsville, Alabama, has developed and patented the Thermal Destruction and Recovery (TDR) process to treat materials containing both organic and inorganic compounds. The TDR employs high-temperature gasification/vitrification. The system can be permitted as a non-incineration process and has been approved by the State of California as an alternative to incineration for medical waste. In 1995, Kaiser Permanente received a permit for a 1,000 pounds per hour TDR-MED System for its facility in downtown San Diego. The EPA is expected to provide similar approval.

The Retech Division of M4 Environmental Technologies, Inc., of Oak Ridge, Tennessee, has developed the PACT System for vitrification. Waste material is fed into a sealed centrifuge where a plasma torch heats solids to approximately 3200^{o} F and gas headspace to a minimum of 1800^{o}F. Organic material is evaporated and destroyed. Inorganic material is reduced to a molten phase that is uniformly heated and mixed by the centrifuge and the plasma arc. The system was successfully demonstrated under the Site Program in 1991 at the DOE Component Development and Integration Facility in Butte, Montana.

Vortec Corporation of Collegeville, Pennsylvania, has developed the Combustion and Melting System, a fossil fuel-fired process that utilizes a cyclone melter, which is an adaptation of the well-established cyclone furnace technology employed in fossil fuel power plants. DOE has participated in development of this technology since 1985, and a 20-tons-per-day pilot-scale test facility has been processing non-hazardous industrial waste since 1988. The vitrified product passes the TCLP standards. A demonstration test of the Vortec system is planned for the DOE Paducah, Kentucky, site during 1997.

Ferro Corporation of Independence, Ohio, has developed a Joule-heated melter. A small pilot unit was tested under the DOE SITE program, processing the Simulated Soil Matrix IV (SSMIV). The unit processed a mixture of 67 percent SSMIV and 33 percent glass former, and produced glass at the rate of 17 pounds per hour. The product passed the TCLP tests.

Duratek, Inc., of Columbia, Maryland, has developed slurry-feed Joule-heated melter systems that have been used in low-level and low-level mixed waste demonstrations at DOE-Fernald and SRS. Duratek also participated in the Hanford LLW Vendor Testing Program using two melters located at Catholic University of America. Duratek is teamed with BNFL to provide privatized vitrification services for treating Hanford LLW.

Toxgon Inc., of Seattle, Washington (formerly Penberthy Electromelt International, Inc., now under new management), has developed both cold-top and hot-top Joule-heated melter systems for various waste treatment applications. Under the former Penberthy management, the company participated in the Hanford LLW Vendor Testing Program. Toxgon has recently installed a Joule-heated melter for ATG, Inc. at Richland, Washington, near the Hanford Site for LLW vitrification.

Roger Ek and Associates, of Issaquah, Washington, is an engineering consulting company specializing in waste vitrification and thermal treatment technologies. Roger Ek and Associates designed and built a facility for vitrification of electric-arc furnace ash Resource Conservation and Recovery Act (RCRA) waste at the Oregon Steel Company in Portland, Oregon. Roger Ek also provided engineering support for design and building of the Vectra Joule-heated melter used in the Hanford LLW Vendor Testing Program and provided design and engineering support for installation of the Toxgon, Inc., Joule-heated melter for ATG, Inc..

U.S. Department of Energy Albany Research Center, (formerly USBM Albany Research Center) in Albany, Oregon, has demonstrated carbon electrode melter technology for treatment of low-level mixed waste at the INEL and for vitrification of LLW for Hanford TWRS. The Albany Research Center also developed and demonstrated a process for preparing dry prereacted melter feed from Hanford liquid LLW. The carbon electrode melter is a robust and promising technology for treatment of mixed wastes containing components that are difficult to vitrify in Joule-heated melters.

Westinghouse Science and Technology Center, Pittsburgh, Pennsylvania, has developed commercially available plasma torch technology for various waste thermal treatment applications. Westinghouse has demonstrated both calcination and vitrification of Hanford LLW simulants at its Waltz Mill Plasma Research Center.

Babcock & Wilcox Alliance Research Center, Alliance, Ohio, has developed cyclone combustion technology for the power industry and also demonstrated cyclone combustion furnaces for waste thermal treatment. B&W participated in the Hanford LLW Vendor Testing Program, demonstrating a cyclone combustion furnace for LLW vitrification.

Stir Melter Inc., of Perryville, Ohio, has developed stirred Joule-heated melters for waste vitrification. Stir Melter built a DWPF pilot-scale stirred melter for demonstration testing at the SRS. Although never used, this melter is still at the SRS TNX facility. Stir Melter also has a small stirred melter at Clemson University's DOE/ Industrial Laboratory for Vitrification.

Science Applications International Corporation, of La Jolla, California, has developed the Plasma Hearth Process (PHP), which uses a DC transferred arc plasma torch with the current discharge effected between a high voltage electrode (inside the torch) and a molten pool of waste maintained at ground potential. Plasma gas temperatures are estimated to reach as high as 10,000°C. Additional heat for melting is provided by the Joule-heating effect as the electrical current passes through the melt. The primary functional units of the PHP system are the feed system, plasma chamber, slag metal removal system, secondary combustion chamber, and air pollution control system. The features that make the PHP process particularly attractive include:

(1) the ability of the process chamber to accept whole drums of waste;

(2) little or no front-end handling, feed preparation, or pretreatment; and

(3) reduced waste characterization requirements.

A pilot-scale non-radioactive system is now under design as well as testing of a bench scale radioactive system at the Argonne National Laboratory-West (ANL-W) TREAT facility. The pilot-scale unit will have a 1.2 MW torch and a throughput of up to two 55-gallon drums per hour.

Appendix B: Resources

Fernald Vitrification Pilot Plant

General:

1. *Department of Energy: Management and Oversight of Cleanup Activities at Fernald* (Letter Report, 03/14/97)
2. *Film Cooler Design (MWFA9)* Information found on the Internet at http://www.fernald.gov/stcg/needs/oh5.html
3. *Pilot Radon Removal Testing (MWFA10)* Information found on the Internet at http://www.fernald.gov/stcg/needs/oh6.html
4. *Real-time Personnel Monitor for Alpha Contamination* Information found on the Internet at http://www.fernald.gov/stcg/needs/oh2.html
5. *Hydraulic Analysis of the Feed Slurry for System Design Requirements* Information found on the Internet at http://www.fernald.gov/stcg/needs/oh7.html
6. *Fluor Daniel Fernald News Releases: GAO Report Documents No Evidence of Danger & Deceit Fluor Daniel Fernald Supports DOE Silos Project Decision* Date: 03/18/1997. Information found on the Internet at http://www.fernald.gov/news/fluor.html
7. *GAO Report Documents No Evidence of A Danger & Deceit"* Date: 03/18/1997. Information found on the Internet at http://www.fernald.gov/news/pr02.html
8. *Statement on the General Accounting Office Review of the Fernald Environmental Management Project.* Date: 03/18/1997. Information found on the Internet at http://www.fernald.gov/news/pr01.html
9. *DOE-FEMP Office News Releases*
10. *Silos Project Lessons Learned*
11. *Development of High-Temperature Vitrification Capabilities for Integrated Systems Using the Minimum Additive Waste Stabilization Approach*

Occurrence Reports

1. OH-FN-FDF-FEMP-1996-0075, *Vitrification Pilot Plant Melter Breach*
2. ORO-FERM-FEMP-1993-0021, *Unauthorized Modifications to Class A Equipment*
3. ORO-FERM-FEMP-1993-0050, *Flash Fire at the MAWS Project*
4. ORO-FERM-FEMP-1994-0055, *Employee Sprayed with Sodium Hydroxide Solution*
5. OH-FN-FERM-FEMP-1994-0075, *Discovery of Suspect/Counterfeit Bolts*
6. OH-FN-FERM-FEMP-1994-0081, *Hoisting Event at the Vitrification Pilot Plant*
7. OH-FN-FERM-FEMP-1995-0087, *Evacuation of Vitrification Plant Due to High Levels of Carbon Monoxide*
8. OH-FN-FERM-FEMP-1995-0094, *Recommended Refractory Ceramic Fiber Exposure Limits Exceeded*
9. OH-FN-FERM-FEMP-1995-0117, *Subcontract Employee Exposed to Elevated Levels of Crystalline Silica*

10 OH-FN-FERM-FEMP-1996-0003, Exposed 120-Volt Wires Outdoors arc due to Contact with Melting Snow
11. OH-FN-FERM-FEMP-1996-0035, *Lightening Strike Causes Partial Loss of Electrical Power to FEMP Site and Partial Loss of Alarm System*
12. OH-FN-FDF-FEMP-1996-0060, *Energy Isolation (Lockout/Tagout) Procedure Violation*
13. OH-FN-FDF-FEMP-1996-0069, *Slurry Sampling Procedure Violation*
14. OH-FN-FDF-FEMP-1997-0025, *Unauthorized Removal of a Site Security System Component*

Savannah River Vitrification Facility

General

1. *GTS Duratek - About the Company*. Information found on the Internet at http://www.gtsduratek.com/aboutgts.html
2. *CRADA Fosters Vitrification Collaboration*. Information found on the Internet at http://www.wpi.org/uetc/init/aug95/crada.html
3. *GTS Duratek, Inc. DRTK 17.38 Nsdq*. Information found on the Internet at http://www.westergaard.com:8080/Env/drtk5.html
4. *CRADA Fosters Vitrification Collaboration* Information found on the Internet at http://www.wpi.org/uetc/init/aug95/crada.html
5. *GTS Duretek, Inc. DRTK 17.38 Nsdq*. Information found on the Internet at http://www.westergard.com:8080/Env/drtk5.html
6. *Glass as a Waste Form and Vitrification Technology*, 1996, Rodney C. Ewing, John F. Ahearne, Robert H. Doremus, Alexandra Navrotsky, Jean-Claude Petit, Raymond Burka, Dennis DuPree
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8. *Mixed Waste Characterization Treatment & Diposal Focus Area*, August 1996, Department of Energy Office of Science and Technology

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