

**AVS: EXPERIMENTAL TESTS OF A NEW PROCESS TO INDUCTIVELY VITRIFY
HLW INSIDE THE FINAL DISPOSAL CONTAINERS AT VERY HIGH WASTE
LOADINGS**

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ABSTRACT

The design and performance capabilities of the Advanced Vitrification System (AVS) are described, together with the results of experimental tests. The AVS is an in-can melting system in which high-level waste (HLW) is vitrified directly inside the final disposal container.

The AVS container, or module, consists of an outer stainless steel canister and an alumina-lined, inner graphite crucible, which is thermally insulated from the outer stainless canister. The graphite crucible is inductively heated to very high temperatures (up to 1500°C) by an external low frequency (30 Hertz) alternating current (AC) transformer coil. The actively cooled outer stainless canister remains at near ambient temperature. The HLW/frit mixture is fed into the hot graphite crucible, where it is vitrified. After cooldown, the HLW/frit feed and off-gas pipes are disconnected from the top of the module, which is then sealed and readied for shipment or storage. All radioactively contaminated melter components inside the module are disposed of along with the vitrified waste. The graphite crucible also provides a geologically stable barrier for the vitrified product.

The AVS potentially can double HLW loading over that obtained from Joule melters; lower vitrification costs by about half; reduce the number of disposal canisters required by about half; handle diverse waste feeds with high concentrations of problem elements such as chromium and zirconium; and reduce the time needed to vitrify a given inventory of HLW.

The AVS can operate at temperatures up to 1500 °C because its refractory materials are at melt conditions for only a few hours, instead of years required for conventional melters. This permits making a wide range of vitrified products from borosilicate glass to highly leach resistant glass ceramics. The AVS process minimizes the necessity for waste feed blending and eliminates the cold cap, the need to control melt viscosity and electrical conductivity and the requirement for pouring. Since the Advanced Vitrification System is modular, with multiple canister-processing cells, it provides operational redundancy and minimum technical risk. It also eliminates the possibility of a single point failure. Because each AVS module contains a single-use melter, there is no subsequent melter decontamination and decommissioning requirement.

Bench scale tests of the AVS were carried out at the DIAL (Diagnostic Instrumentation Analysis Laboratory) at Mississippi State University. The tests produced 5-inch diameter AVS borosilicate glass logs with simulated HLW loadings of 35 and 50% by weight. The simulated HLW material was supplied by the Department of Energy (DOE) and corresponded to Hanford Envelope D waste. The product glasses met or exceeded DOE's Product Consistency Test (PCT), and the Environmental Protection Agency's Toxicity Characteristic Leaching Procedure

(TCLP) requirements at both HLW loadings. Within the accuracy of measurement, cesium was retained in the product glasses. No appreciable corrosion of the alumina liners inside the graphite crucibles was observed. The amount of crystallinity was small, less than 1% at 35% HLW loading, and less than 5% at 50% waste loading. Crystallinity tests on the 50% HLW loading showed satisfactory stability upon heat treatment after vitrification.

Small-scale lab tests indicate that even higher HLW loadings, in excess of 60%, appear possible. Additional bench-scale tests have been carried out on problematic wastes containing very high concentrations of chromium, zirconium, and bismuth, with excellent durability behavior. The process parameters, design, and costs of a full-scale AVS facility to vitrify the Hanford HLW waste have been preliminarily described. The time to process a given AVS module is 3 days, including heatup, vitrification and cooldown. A total of 6000 AVS modules would be required to vitrify all Hanford waste, a much smaller number than that required using a conventional Joule melter. The AVS facility, with a projected capital cost of about \$239 million, would have 12 process cells, with a capability of producing four disposal modules per day. Assuming waste retrieval or other non-AVS operations were not a constraint—which is probably not the case—the AVS facility could vitrify all Hanford HLW in about 6 years.

OBJECTIVES OF THE AVS PROGRAM

The overall goal of the Advanced Vitrification System program is to develop and demonstrate an advanced technology for vitrifying the high-level waste presently stored at a number of sites in the United States.

The Advanced Vitrification System is fundamentally different from existing vitrification technologies. The AVS directly vitrifies the HLW inside the final disposal container. It eliminates the need for an external melter and it eliminates pouring molten wastes into a stainless steel canister. For the AVS, the outer stainless steel canister is maintained at near ambient temperature during and after the vitrification process. The steel canister is not subjected to the high temperatures of the molten waste. The melting step in the AVS process is carried out in an interior high-temperature graphite/alumina crucible, which is thermally insulated from the outer stainless shell.

The AVS process enables much higher melt temperatures than is possible with conventional joule melters. This in turn permits a higher waste loading and greater tolerance for varied waste chemistry. Higher melt temperatures are possible because the AVS module is used only once and, consequently, the refractory materials operate at such high temperatures for only a few hours, well within the window of performance of existing refractory materials. In contrast, a conventional joule melter is required to operate in a continuous fashion for years. For the joule melter, any failure in the refractory material would necessitate shutdown of the melter and its possible replacement. Thus, the refractory materials in the joule melter must operate at lower melting temperatures to ensure reliable operation. An important process benefit of having a module system like the AVS is that any failure of the refractory material will affect only a single module, and will not significantly affect the processing capability of the vitrification facility.

The Advanced Vitrification System eliminates the need to pour molten glass from the melter into a disposal container. This is significant because a number of pouring accidents have occurred with conventional melters, and this has adversely affected system reliability and operability. The AVS also eliminates the need to maintain a cold cap within the melter, as well as the need to dispose of radioactively contaminated melters.

The specific objectives of the AVS program are to demonstrate that the Advanced Vitrification System will:

- Achieve much higher HLW loadings in vitrified waste products than is possible using conventional melters.
- Require a much smaller number of disposal containers for a given HLW inventory.
- Enable a much wider range of HLW compositions to be vitrified at higher waste loadings than is possible using conventional melters.
- Reduce the amount of HLW pretreatment required for vitrification.
- Significantly reduce the capital investment and operating costs for vitrifying HLW.
- Significantly reduce the campaign time required to vitrify a given inventory of HLW.
- Achieve excellent durability performance of the vitrified waste product, as measured in waste form testing (e.g. PCT, TCLP, crystallinity, homogeneity, etc.).
- Provide increased system reliability and redundancy.
- Provide enhanced environmental protection over geologic time periods, e.g. hundreds of thousands of years.

With regard to higher waste loadings in the first objective, conventional joule melters generally achieve a HLW loading of about 25% (mass of the HLW in the glass divided by total mass of glass). Based on initial tests, the AVS process, due to its capability to operate at substantially higher melt temperatures, has achieved HLW loadings of 50% and above in borosilicate glass. Very high waste loadings, ~ 75%, have also been produced. However, these were in a glass ceramic waste form.

The second objective of producing fewer disposal containers for the same quantity of waste is linked to the first objective. The higher waste loadings result in a smaller number of disposal canisters, even when the penalty in fill volume due to the presence of the graphite/alumina crucible in the AVS module is taken into account.

The third objective is related to two fundamental advantages offered by the AVS. First, the short exposure time and higher temperature for the AVS refractory materials allows more aggressive HLW/Frit feeds and less concern about problem elements. Second, since there are no electrodes

in the melt, their corrosion is not a problem, so that feed compositions that would corrode conventional electrodes can be vitrified in the AVS.

The fourth objective is related to the third objective. Because the AVS can vitrify a wide variety of HLW compositions it not necessary to pretreat the HLW to reduce concentrations of elements, such as chromium or zirconium. Moreover, since the AVS process can operate over a wide range of pH from strongly acid to strongly alkaline, the pretreatment to control pH can be much simpler. With the AVS, demonstrating that pretreatment costs can be substantially reduced will directly reduce total life cycle costs from those expected for a conventional vitrification systems.

The fifth objective, lower capital and operating costs, appears possible with the Advanced Vitrification System because of its higher HLW loading in the vitrified waste product, the small number of disposal canisters and the consequent lower repository fees, the greater simplicity of the vitrification operation and equipment and the reduced amount of pretreatment.

With regard to the sixth objective, the vitrification campaign time for the Advanced Vitrification System should be considerably shorter than that for conventional melters, because it has a much faster process time, higher waste loading, and smaller number of disposal canisters. In addition, the potentially improved reliability and redundancy of the Advanced Vitrification System would reduce lost time associated with melter malfunction, repairs and replacement.

With regard to the seventh objective, the AVS process, as described later, minimizes the variability of the vitrified waste form, ensuring that the product is homogenous and predictable. Tests of AVS waste forms have shown excellent durability performance, both PCT and TCLP, as well as low crystallinity and excellent homogeneity.

The eighth objective, increased system reliability and redundancy, is achieved by the inherent nature of the AVS. A full-scale AVS facility would have 12 independent process cells. Failure of a single cell's process equipment (e.g., inductive heating coil, cooling system, etc.) will affect only that cell and would have a limited affect on the overall production rate. Moreover, the failed equipment in a cell, in most instances, could be quickly replaced. This contrasts with conventional melters, where the failure of the melter would stop the production of canistered waste from the facility for a lengthy period. If the refractory material inside a particular AVS module were to fail, in most cases, this can be easily detected before any breach of the module. Such a failure would only affect that module and not the subsequent operation of the AVS process cell. The failed module would simply be removed and a new module inserted into the process cell. Thus, even for a refractory material failure, there should not be a significant impact on the production rate from a process cell.

The ninth objective is to enhance environmental protection by increased containment and isolation of the vitrified waste product. The AVS disposal modules provide this enhanced containment and isolation with sealable, high-integrity graphite crucibles. After sealing, the graphite crucibles provide a geologically stable barrier, isolating the vitrified waste from the environment. The graphite barrier will not corrode or dissolve, even after millions of years. In contrast, the outer stainless steel canister that encloses the vitrified waste form conventional

melts will corrode through in approximately 1000 years, far short of the period during which the radioactivity in the vitrified waste is still hazardous.

DESCRIPTION OF THE AVS SYSTEM

Figure 1 shows the basic AVS Module. Its outer stainless steel canister is equal in diameter (61cm) length (4.5m) and wall thickness (1 cm) to the dimensions for the conventional pour-type canister. Moving radially inward from the inner surface of the stainless canister, there is a 1-centimeter layer of graphite fiber thermal insulation, then a graphite crucible with a wall thickness of 2.5 centimeters. The graphite crucible has an inner liner of alumina (Al_2O_3) ceramic, with a thickness of 0.5 centimeters.

The AVS modules are manufactured and shipped as fully assembled units to the vitrification facility. After arrival, the modules are inspected and made ready for processing.

The AVS process is illustrated in Figure 2. The empty module is transferred to one of the shielded processing cells in the facility, where the HLW feed and off-gas pipes are connected to it using remote handling equipment. The empty graphite crucible inside the modules is then inductively heated to high temperature using an external low frequency AC coil that encloses the module.

The temperature of the graphite crucible is raised to the desired process temperature (e.g. $1,350^{\circ}C$) while the outer stainless canister is maintained at near ambient temperature (e.g. $\sim 100^{\circ}C$) with forced cooling. The thermal insulation between the hot graphite crucible and the cool stainless canister keeps the thermal conduction heat flow loss from the hot graphite crucible to a loss level, e.g. 2 to 3 watts per square centimeter of surface area.

A low AC frequency, nominally 30 Hertz, heats the graphite crucible. The low frequency allows the AC magnetic field to penetrate the outer stainless canister with minimal skin effect. If the induction AC frequency were considerably greater than 30 Hertz, the AC skin effect on the stainless canister would prevent the AC magnetic field from penetrating the outer canister. However, even with a low AC frequency coil, the stainless steel canister is inductively heated by the transformer coil. For the module design illustrated, with a 1-centimeter wall thickness for the stainless canister and a 2.5-centimeter thickness for the graphite crucible, the heating rate (watts/cm² of surface area) in the stainless canister is approximately twice that in the graphite crucible. This is not a problem, however, since cooling of the stainless canister is readily accomplished, and the cost of the process energy is relatively small, even when the parasitic I^2R losses in the stainless canister are included.

After the graphite crucible reaches desired process temperature, feeding of the HLW/frit mixture into the hot crucible begins. The HLW/frit mixture can be fed as a dry powder or a liquid slurry. The melt and fill method chosen for the AVS process is termed the "Hot Hohlräum Melt" (HHM) method.

Figure 3 illustrates how the HHM method works. The empty graphite crucible forms a "hot hohlraum" inside of which radiant energy is transported at much higher intensity than the

thermal conductive heat flux that leaks through the insulation that encloses the graphite crucible. At 1,350°C, the radiant heat then is on the order of 35 watts per cm² of crucible surface, as compared to the 2 to 3 watts per cm² that leaks through the insulation.

As a result, the walls of the empty portion of the crucible are at virtually the same temperature. The HLW/frit feed dropping through the hot hohlraum region is rapidly heated. It forms a melt pool at the bottom of the crucible. As the feed process continues, the melt surface rises. The crucible is nominally filled to 90% or greater of its original empty volume when filling is complete. At the design feed rate of 10 inches per hour, the 4.5 meter long crucible is 90% filled in 16 hours.

The AC inductive heating coil is positioned to heat the portion of the graphite crucible that is above the melt surface, and not the portion that is below the surface. The resultant downward conductive heat flux through the vitrified waste and the heat loss through the thermal insulation that surrounds the portion of the crucible that is below the melt surface, results in a rapid cooling of the waste. The molten HLW/frit feed reaches the freezing point only a few inches below the melt surface and continues to decrease in temperature with increasing distance below the melt surface. As a result, the residence time of the waste material in the molten state is very short, on the order of 1 hour, as compared to the tens of hours in a conventional melter. The short melt residence time for the AVS system minimizes the rate of cesium loss, and helps to insure product homogeneity. Moreover, the rapid cooling rate of the solidified waste in the region below the liquid/solid interface helps to minimize crystallinity in the solid waste product.

The inductive heating region rises along the module at the same rate as the melt surface, ensuring that the heating zone and melt surface always maintain their relative geometric positions. The motion of the heating zone can be either provided by physically moving the inductive heating coil, or by using a segmented stationary coil, with the various segments sequentially energized to generate the moving heating region.

The Hot Hohlraum Melt method was selected as the best of the three heating options investigated for the AVS system. Figure 4 shows the three options. The Uniform Melt (UM) method, in which the module is filled with ambient temperature HLW/frit feed and then inductively heated, was dropped because the volume shrinkage of the solid HLW/frit feed during melting (due to the voids between particles) resulted in a module fill fraction that was too low (i.e. ~60% compared to the desired 90%).

The second melt/fill option is the Zonal Melt (ZM) option. In the ZM option (Figure 5), only a local portion of the HLW/frit load inside the module is inductively heated. (More accurately, a local portion of the graphite crucible is inductively heated to the melting point.) The molten zone moves slowly upwards inside the module as additional HLW/frit feed enters the crucible. As the molten zone moves upwards, it leaves behind a rising log of solid vitrified waste. When the molten zone reaches the top of the crucible, the module fill fraction is 90% or greater.

While the ZM method can achieve a high module fill fraction, the Hot Hohlraum Melt method has a number of significant advantages over it, as outlined in Figure 6. The most important advantage of the Hot Hohlraum Melt method is the minimization of foaming. In the ZM method,

there is a large inventory of cold unheated feed above the hot melt zone, which can act as a source of gas when heated. This gas then has to percolate through the cold material above it. This creates a potential for foaming and entrainment of aerosoled material in the feed and off gas piping.

In contrast, in the Hot Hohlräum Melt method, all of the gas from the HLW/frit feed is released quickly as the feed drops through the hohlräum and contacts the melt surface. There is no impediment to the gas leaving the module hot zone, and no buildup of foaming material. Initial experimental tests of the Hot Hohlräum Melt process indicate that it has no foaming problem. Accordingly, for this and the other reasons indicated in Figure 6, the Hot Hohlräum Melt method has been selected as the best process approach for the AVS system.

Table I summarizes the principal parameters of the AVS module. Of particular interest is the 1,250 kg of HLW loading when the module is filled with 50% HLW. With a lower silver content in the waste feed, as is the case for most of Hanford's wastes, lab testing showed that a waste loading of 62% would probably be achievable. At 62% waste loading, the amount of HLW would increase to 1,570 kg, an amount more than twice that for a conventional pour canister with the 25% waste loading obtained with from conventional waste.

Also of interest, is the low cost of electric energy to process an AVS module. The average cost is estimated at \$1,000 per module, using a conservative electricity cost of 10 cents per KWH. This cost is small compared to the almost 1 million dollars per module required for storage, transport and repository fees.

Figure 7 shows the various sub-systems involved in processing AVS modules. Certain of these sub-systems are not unique to the AVS and would be required for any vitrification system. These include the HLW feed system, the off-gas handling system, and diagnostic systems. The module heating and cooling systems use conventional, existing technology. The module insertion and removal systems involve simple mechanical movement mechanisms. The module closure sub-system is unique to the AVS, and would have to be developed.

EXPERIMENTAL TESTS OF THE AVS PROCESS AND VITRIFIED WASTE FORM

Two phases of tests have been carried out to determine the performance of the AVS process in producing vitrified waste forms. In Phase 1, scoping vitrification tests on a broad range of HLW compositions and loadings were conducted to determine potential operational regimes for the AVS system. In Phase 2, vitrification tests were carried out using a specified Envelope D waste composition supplied by DOE to determine limits on waste loading, and to characterize the vitrified waste product in greater detail than was done in Phase 1.

The Phase 1 and Phase 2 tests were carried out both at the laboratory scale and the bench scale. The laboratory scale tests involved small crucibles (~2 inch diameter) using conventional high temperature furnaces. The bench scale tests involved 5-inch diameter, insulated graphite/alumina crucibles. An inductive heating system was used, similar to that proposed for the AVS System.

Figure 8 shows a photo of the Phase 2 bench scale test stand at DIAL. The Phase 2 stand is essentially a reconstituted version of the stand used for the Phase 1 tests, which were conducted at Argus Remediation, Inc. The test stand utilizes a 5-inch ID, 17-inch long graphite crucible, with a 1/4th inch wall inner alumina (Al_2O_3) liner. The crucible is insulated with graphite fiber thermal insulation and enclosed inside a quartz tube with an inert argon atmosphere. It is inductively heated by an external 1 kilohertz AC transformer coil.

The graphite/alumina crucible is first filled with ambient temperature HLW/frit mixture and then inductively heated at an appropriate rate to ensure that foaming, or an excessive rate of gas output, will not occur. (This heating protocol corresponds to the Uniform Melt method discussed previously). After the HLW/frit mixture has reached the desired melt temperature, it is held at that temperature for an appropriate time, and then allowed to cool down. The melt temperature and hold time values are controlled so as to reflect the particular composition being vitrified.

Figure 9 shows the log of the bench-scale vitrification test carried out in the phase 1 tests. A total of 19 bench-scale tests were run for a range of simulant composition. In particular, high bismuth, high chromium, and high zirconium compositions were successfully vitrified, at waste loadings of 100% simulant and no frit or other additives.

Figure 10 shows a photo of a typical vitrified log produced during the Phase 1 tests. The composition was 70% simulant with 30% added frit. The melt temperature was 1,450°C, and the hold time at temperature was 4 hours. The log was homogeneous in appearance and the PCT leach results were independent of position, whether top, bottom, or middle, center or sides. Note that there is essentially no attack of the alumina crucible after 4 hours at 1,450°C, except for a very small notch at the contact point at the melt meniscus. This notch, which is small in depth, would not be present in the continuously filled Hot Hohraum Melt method, because the meniscus of the melt would be moving upwards continuously.

Moreover, in the Hot Hohraum Melt process, the maximum period of time that any part on the alumina liner would be exposed to the melter HLW/frit mixture would be well under one hour, as compared to the 4-hour hold time for the Phase 1 bench-scale tests.

PCT results for the Phase 1 bench-scale vitrified product are summarized in Figure 11. For all compositions tested, the PCT leach results are much less than those for the EA glass, typically one to two orders of magnitude smaller. Leach rates did not significantly vary as a function of position within the vitrified log.

In the Phase 2 experimental tests, an Envelope D waste simulant, which was supplied by DOE, was used. The composition of this simulant is shown in Table 2. The silver content of the simulant is atypically high, much greater than that present in virtually all of the Hanford tanks.

A log of the Phase 2 tests, both at the laboratory scale and the bench scale, is shown in Figure 12. As specified in the statement of work for Phase 2, the objective was to produce and test borosilicate glass vitrified waste forms at two different HLW waste loadings, 35% HLW content and the highest waste loading that satisfied the various applicable criteria for the waste product. The definition of HLW waste loading followed DOE specification, where the sodium oxide and

silica content in the waste feed is subtracted from the HLW mass. The DOE formula for HLW loading is —

$$\text{Waste Loading} = 100 \times \text{Mass of glass} - ((\text{Mass of glass formers added} + (\text{Mass Na}_2\text{O} + \text{Mass Si}_2\text{O in waste})) / \text{Mass of glass})$$

The laboratory-scale tests shown in Figure 12 were used to help guide the processing parameters (e.g. melt temperature, hold time, type of frit, etc.) for the later bench-scale tests. In addition, for the bench-scale test at maximum HLW loading, the lab-scale tests helped to define the value of loading of the Envelope D simulant that would meet the appropriate PCT, TCLP, and other criteria.

Based on the lab-scale tests, a maximum HLW loading of 50% was chosen for the bench-scale test. Figure 13 shows the PCT results for the 35% and 50% waste loadings. The PCT leach rates for the AVS products are more than an order of magnitude lower than those for the reference glass, even at the maximum waste loading.

Figure 14 shows the TCLP results for the bench scale products. Except for silver, the TCLP leach rates are substantially below the Environmental Protection Agency's Universal Treatment Standards (UTS) limits for both the 35 and 50% waste loadings. The silver TCLP leach rate at 50% loading was only slightly less than the UTS limit; at 35% loading, the silver leach rate was well below the UTS limit.

The silver content in the Envelope D simulant was much higher than that in the actual waste in the vast majority of Hanford tanks. If the silver TCLP rate had not been the limiting factor in determining the maximum HLW loading the lab scale tests indicated that considerably higher HLW loading could be achieved, e.g. 62% or more.

The higher waste loading appears feasible for the bulk of the Hanford waste, which has a very low silver content. For the small portion of the waste that has high silver content, the waste loading could be kept at ~50% or alternatively, the waste could be blended with wastes having low silver content, allowing the production of vitrified waste products at a HLW loading >50%.

The product glasses were examined using a variety of techniques, including visual, X-Ray Diffraction and scanning electron microscope to determine the type and amount of crystallinity present. The volume percent of crystals in the 35% HLW loaded glass was low, on the order of 1%. The volume percent at the 50% HLW loading was somewhat higher, and acceptable, in the range of 3 to 5%. Spinel was the only crystalline phase detected.

Six samples from various locations on each vitrified glass log were tested. The locations were the top, middle and bottom regions at the centerline of each log and the top, middle, and bottom regions at the side of each log. The test results on PCT, TCLP, and crystallinity performance indicated that the logs were homogeneous, within the limits of analytical capability.

In addition to the PCT, TCLP, and crystallinity tests, chemical analyses of the composition of vitrified logs were carried out, along with analyses of the chemical composition of the off gases

as a function of temperature during the vitrification process. Chemical composition was uniform throughout the vitrified glass product and met the standard for boron content ($\geq 5\%$).

No foaming problems were encountered during the vitrification process, even though the bench scale tests were carried out using the uniform melt (UM) method in the same fashion as the Phase 1 tests. No appreciable corrosion of the alumina liners inside the graphite crucibles was observed at the $1,350^{\circ}\text{C}$ melt process temperature. The vitrified glass logs retained essentially all of the cesium originally present in the feed, to within the limits of the analytical capability. More accurate analytical methods are needed to determine the fractional loss of cesium.

A continuous fill experiment was performed using the Hot Hohlräum Melt (HHM) fill method. The apparatus for this experiment, termed COFFEE (Continuous Feed Fill Experimental Equipment) is shown in Figure 15. Dried HLW/Frit simulant (dried to 450°C in an oven) was fed at ambient temperature into the top of a 1.75-inch ID, long alumina crucible. A short section of the crucible, about 5 inches in length, was held at the melt process temperature of $1,350^{\circ}\text{C}$ (the hot zone was heated by a close fitting annular resistance heated furnace). The temperature of the alumina crucible above and below the 5-inch hot zone monotonically decreased towards ambient values.

The COFFEE test started with the alumina crucible in an empty condition, with the 5-inch hot zone located at the bottom of the crucible. As the dried waste simulant was fed into the top of the crucible, the level of the vitrified waste inside the crucible continuously rose, simulating the moving inductive heating zone in the HHM fill method. The rate of rise of the 5-inch hot zone matched that of the simulant feed rate so that the melt surface always remained at the mid-plane of the 5-inch hot zone.

As the feed process continued, an ever lengthening glass log was produced, with a melt region of a constant ~ 3 inches in thickness, and an ever longer length of solid glass log beneath the melt region.

The COFFEE test was carried at a liquid fill rate of 5 inches per hour – $\frac{1}{2}$ that of the design 10-inch per hour fill rate for the full-scale AVS module – for a period of 4 hours. This produced a glass log of 20 inches in length with an aspect ratio (length/diameter) of 12/1. The full-scale AVS Module has an aspect ratio of 8/1. Tests on the COFFEE log found that it was homogenous and uniform in properties along the 20-inch length.

The COFFEE fill process was semi-continuous, that is, not fully continuous. Small batches of dried feed were added every 5 minutes (equivalent to a melt zone height increase of 0.5 inches). This allowed observation of the melt surface between the batch additions. Immediately after the addition of the fresh batch of feed, there was a small amount of surface bubbling as the feed decomposed and produced off gases. However, the bubbles were small, on the order of $\frac{1}{4}$ inch diameter at maximum, and there was no appreciable foaming. The surface became quiescent after a minute or so, leaving a few patches of dark solids floating on it, much as pieces of solid lava float on a lava lake. After another minute or so, these dark patches disappeared leaving only a smooth, uniformly glowing, non-bubbly surface that persisted until the next batch addition.

Based on these observations, it appears that the surface effects would be even less for a continuous fill procedure than were observed for the semi-continuous one. In addition, there do not appear to be any serious problems in increasing the fill rate to the design value of 10 inches per hour, twice that performed in the COFFEE experiment.

DESCRIPTION OF THE FULL-SCALE AVS FACILITY

Figure 16 shows a conceptual flow sheet for a full-scale AVS facility producing vitrified waste at 50% HLW loading. The material flow quantities are normalized to a glass output of 1.5 metric tonnes per day. Since the HLW loading in the AVS glass is 50%, the actual weight of HLW in the glass is twice that which would be achieved with a 1.5 metric tonnes/day, 25% HLW loading produced by a continuous melter.

Figures 17 and 18 show the process-module flow and floor plan for a full-scale AVS facility with 12 process cells (that is, 12 independent cells for processing 12 modules in stages simultaneous processing). Each process cell can produce a module of vitrified waste in a nominal process time of 3 days to process (the actual time will probably somewhat less, probably as little as 2 days). The 12 process-cell AVS facility would have a total output of 4 modules per day. At a nominal 3 metric tonnes of glass per module and 50% HLW loading, this would correspond to a configuration rate of 6 metric tons of HLW per day, or 1,800 tons per year on a 300 day year basis. Such a facility could vitrify the ~10,000 tons of HLW at Hanford in about 6 years. However, other factors, such as waste retrieval and pretreatment rate probably would control the actual vitrification rate, and would extend the time needed to fully vitrify the Hanford high-level wastes.

The capital cost of the 12-cell AVS vitrification facility is projected to be \$239 million. The life cycle costs are estimated to be about \$470 per kg of HLW vitrified, based on a 15 year campaign and a total inventory of ~10,000 metric tonnes at Hanford. These life-cycle costs appear to be considerably less than those projected using conventional melter technology. These life-cycle cost estimates do not include repository fees. Since the number of AVS disposal containers will be approximately one-half that from a conventional melter, the AVS repository fees will be much less. The savings from a much shorter mortgage on the cleanup campaign would equate to billions in savings. One PNNL report estimates \$500 million in overall savings for each percentage point increase in waste loading.

TECHNOLOGY BASE FOR THE AVS SYSTEM

The AVS system has a strong technology base for its module components and sub-systems. A summary of the technology base is shown in Figure 19. UCAR Carbon Company, Inc., a RIC owner, (UCAR) now manufactures graphite cylinders of the size and wall thickness required for the full-size AVS module (Figure 20). While not currently producing cylinders of the desired 15-foot length, the manufacturing process can be modified to produce cylinders of full length, or alternately, the full-length crucible can be manufactured by joining several shorter-length cylinders together. The joints can be screw-type or cemented together using graphite cement. Cemented joints have been shown to be even stronger than the base graphite cylinders.

High-quality, high-integrity alumina liners are currently produced, but not in sufficient diameter and length for the full-scale AVS modules. Scale up of the alumina liner diameter to the full-size module appears feasible, but will require some development work. It may be necessary to join shorter lengths of full-diameter alumina liners to achieve the total 15-foot length desired. Alternatives to the solid alumina liner/crucible approach are being investigated, including plasma sprayed and CVD (chemical vapor deposition) coatings on graphite, as well as CVD impregnated alumina-fiber liners.

It should be noted that there is only minimal interaction between the molten glass and the graphite crucible, even at high temperatures. In the Phase 1 program, for example, some tests were inadvertently run at higher temperatures than intended. In one such test, the melt was held at 1,600°C, much higher than planned for normal AVS operation.

As a result of this very high temperature, the alumina crucible was corroded through at the meniscus (i.e. the point at which the melt surface contacts the alumina) and the molten glass was in direct contact with the underlying graphite. Even at this temperature, and for an exposure time of up to 4 hours, the graphite crucible exhibited only a very small amount of localized attack. A small portion of the graphite along the meniscus line was eaten away to a maximum depth of ~3 millimeters (~120 mils). Accordingly, the alumina liner, while important from the standpoint of minimizing graphite reaction with the melt, is not a critical component from the safety standpoint. Local penetration or failure of the alumina will not affect the operation of the melt/fill process, nor will it affect the acceptability of the completed AVS module.

The other module components, i.e. the thermal insulation and the outer stainless steel canister, are already commercially available. The inductive heating and module cooling systems use existing conventional technology.

Accordingly, essentially all of the module components could be procured today, except for the alumina liner, which will require some development work. However, there does not appear to be any problem in achieving a satisfactory alumina liner. The module heating and cooling systems can be designed using a currently available commercial technology.

Design of the feed and off-gas systems for a full-scale AVS system will require tests on bench and pilot units to determine the optimum feed method and the nature of the off gases, which will depend to a substantial extent on the feed composition.

The AVS off-gas and feed system should be designed so that they can be handle a wide range of feed components of the type found at the cleanup site. There does not appear to be any special difficulty in doing so, but more information is needed on what type of feeds will be handled by a full-scale AVS system and what the nature of their off-gasses will be.

Figure 21 shows a summary of the major development steps leading to the full-scale AVS facility with the development program shown, the AVS system could begin vitrifying HLW at Hanford by 2008 AD.

SUMMARY AND CONCLUSIONS

In summary, the AVS system has the potential to significantly increase the HLW loading in vitrified waste products as compared to conventional melters, and consequently, significantly reduce the number of canisters sent to the repository to dispose of a given inventory of high-level waste.

Bench-scale tests have produced vitrified 5-inch diameters borosilicate glass logs containing simulated HLW loadings of up to 50%. These tests used a DOE-supplied, Envelope D waste simulant. The logs exhibit PCT leach rates more than an order of magnitude lower than the reference Environmental Assessment (EA) glass and meet TCLP-UTS standards. The logs are homogeneous in composition and properties and have low crystallinity, less than 5% even at the highest waste loading. Based on laboratory-scale experiments, even higher waste loading appears achievable for waste having a lower silver content, which is the case for the bulk of the Hanford waste. Compared to the ~25% HLW loading achieved with conventional melters, this would result in a reduction in the number of disposal canisters sent to the repository by about a factor of 2.

Bench-scale vitrification tests on other waste compositions indicate that the AVS system can vitrify a very wide range of waste feeds. This includes waste feeds with high concentrations of problem elements such as chromium and zirconium, which are very difficult to vitrify in conventional melters. Moreover, the amount of pretreatment required for the AVS system is much less than that for conventional melters.

In addition to the environmental protection offered by the very durable AVS waste glass form, the AVS module provides an additional protective barrier. The graphite crucible inside the outer stainless steel canister holds the glass in a geologically stable (millions of years), non-corroding container, which should isolate the glass from the environment long after the outer stainless canister has corroded away.

The AVS system is simple to operate and should be highly reliable and redundant. The refractory materials inside the AVS module operate at high temperatures for only a few hours, not years as with the conventional melter, so that the chances of failure are greatly reduced. Moreover, if a module were to fail, it would not stop the operation of the AVS facility – it would be quickly removed and the facility would recommence operation. There are no contaminated melters requiring D&D. All of the contaminated components inside the module are disposed of along with the waste glass in the module.

A strong commercial technology base for the module components and process sub-system already exists. The graphite crucible, thermal insulation, and outer stainless canister can all be manufactured by existing equipment. Engineering development of larger-diameter alumina crucibles is required, but appears achievable in a year or two. The low frequency AC inductive heating system and the forced convection cooling system can be built using existing commercial technology.

The AVS system could be in operation for Hanford waste by 2008 AD.