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Evaluation of Melter Technologies for Vitrification of Hanford Site Low-Level Tank Waste - Phase 1 Testing Summary Report

C. N. Wilson, Editor
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Abstract: Following negotiation of the fourth amendment to the Tri-Party Agreement for Hanford Site cleanup, commercially available melter technologies were tested during 1994 and 1995 for vitrification of the low-level waste (LLW) stream to be derived from retrieval and pretreatment of the radioactive defense wastes stored in 177 underground tanks. Seven vendors were selected for Phase 1 testing to demonstrate vitrification of a high-sodium content liquid LLW simulant. The tested melter technologies included four Joule-heated melters, a carbon electrode melter, a combustion melter, and a plasma melter. Various dry and slurry melter feed preparation processes also were tested. The technologies and Phase 1 testing results were evaluated and a preliminary technology down-selection completed. This report describes the Phase 1 LLW melter vendor testing and the tested technologies, and summarizes the testing results and the preliminary technology recommendations.

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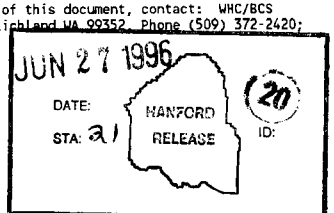

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Many Hanford Site staff and others contributed to the Phase 1 Tank Waste Remediation System (TWRS) Low-Level Waste (LLW) Melter Vendor Testing Program. A list of the program activities and significant contributors is provided below. Listed contributors were Westinghouse Hanford Company (WHC) employees unless otherwise indicated.

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A few of the many program contributors listed above were also contributing authors for draft sections of the present Phase 1 Summary Report. Drafts for the 4.x subsections describing the melter technologies and Phase 1 tests were prepared by the WHC cognizant engineer (identified above) for each of the vendors. Section 3.0 on the LLW simulant was drafted by S. E. Kelly and J. W. Shade. The first draft of Section 5.0 on product glass evaluation was written by J. W. Shade. Section 6.0 on offgas and mass balance results was written G. A. Whyatt (PNNL). Section 7.0 on the process flowsheet studies was drafted by A. F. Manuel. Section 8.0 summarizing the LLW vitrification facility configuration study by Fluor Daniel, Inc. was drafted by W. C. Eaton. Section 9.0 on safety and environmental assessments was written by C. E. Leach and J. M. Colby. The lead author (C. N. Wilson) was assisted by S. R. Nelson (BCS Richland, Inc.) in editing this report.

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EVALUATION OF MELTER TECHNOLOGIES FOR VITRIFICATION OF HANFORD SITE LOW-LEVEL TANK WASTE - PHASE 1 TESTING SUMMARY REPORT

1.0 SUMMARY

Following negotiation of the fourth amendment to the Tri-Party Agreement (Ecology et al. 1994), the Hanford Site Tank Waste Remediation System's (TWRS) baseline process for immobilization of the low-level waste (LLW) stream was changed from grout to vitrification. New Tri-Party Agreement milestones established for TWRS LLW immobilization included: (1) begin LLW melter testing with simulants (September 1994); and (2) complete melter feasibility and system operability tests, select reference melter(s), and establish reference LLW glass formulation that meets complete systems requirements (June 1996). To comply with the revised Tri-Party Agreement requirements to begin melter testing by September 1994 and select a reference LLW melter technology by June 1996, a two-phased technology demonstration program was initiated in 1994 by Westinghouse Hanford Company (WHC) with vitrification technology vendors to support selection of a reference melter technology for LLW vitrification. Phase 1 testing with seven vendors, preliminary technology evaluation, down-selection, and recommendations for Phase 2 testing were completed during fiscal years (FY) 1994 and 1995. The Phase 1 LLW melter vendor tests, testing results, and recommendations are summarized in this report.

The seven vendors selected for Phase 1 testing demonstrated a variety of melter technologies and melter feed preparation processes. These technologies and Phase 1 testing results are summarized below in alphabetical order for each of the seven vendors.

Babcock & Wilcox (B&W) demonstrated a slurry-fed cyclone combustion melter system at its Alliance Research Center in Alliance, Ohio. The B&W vitrification technology is based on cyclone combustion technology developed for large fossil fuel-fired boilers used in the electric utility industry. Slag is typically produced as a vitreous combustion ash by-product as a result of mineral impurities in coal. The cyclone furnace is a water-cooled, horizontal cylinder attached to the wall of the main furnace cavity. When operating, a layer of frozen glass 'skull' forms on the walls of the cyclone furnace and inhibits corrosion and erosion of the furnace. For waste vitrification applications, slurry feed is injected onto the cyclone wall where it melts and flows down the cylindrical walls and is collected in the bottom of the cyclone. Glass drains from the cyclone through a notch in the back baffle of the cyclone to a sump in the main furnace cavity. Following minor startup difficulties, a 24-hour steady-state demonstration run was completed at a production rate of ~0.6 metric ton (0.6 tonne)/day of glass. Volatile component and offgas entrainment losses during the B&W demonstration were among the highest measured in any Phase 1 test. B&W expects that lower volatility and entrainment losses could be achieved with equipment modifications and with larger full-scale units up to 100 tonne/day capacity as proposed for the LLW vitrification facility.

Envitco, Inc. (Envitco) of Toledo, Ohio, demonstrated a high-temperature Joule-heated melter with spray-dried and slurry feeds. The Envitco melter technology uses a water-cooled shell and relatively thin refractories in glass contact areas resulting in the formation of a glass skull layer that Envitco believes will reduce refractory wear and extend melter life. The Phase 1 testing was conducted in the Envitco EV-16 melter at Clemson University, Clemson, South Carolina. The EV-16 melter is a small unit with a 0.21-m^2 melt area and a 0.5 to 1 tonne/day capacity. The EV-16 melter is fired by four sidewall molybdenum rod electrodes and uses a proprietary mechanically controlled drain system. Envitco proposes to use a 50 tonne/day design with slanted top-entering electrodes and overflow side drain system for the full-scale LLW vitrification facility melters. Dry feed for Phase 1 testing was prepared from slurry at the Hosokawa Bepex Corporation of Minneapolis, Minnesota, using the Bepex Unison[1] spray-drying process. The dry feed melter demonstration was conducted with full cold-top batch coverage resulting in the lowest volatile component losses measured in any Phase 1 test. A steady-state glass melt rate of ~110 kg/m^2/h achieved with the dry feed was also the highest melting rate per unit area achieved by any of the Joule-heated melters. Following the dry feed melter demonstration, melting with direct slurry feed was demonstrated. With the exception of a melt 'reboil' incident at the end of the dry feed segment, and a cooling system interlock trip during the slurry feed segment, the melter operations went smoothly.

GTS Duratek, Inc. (Duratek) of Columbia, Maryland, demonstrated a low-temperature Joule-heated melter technology that uses Inconel[2] plate electrodes, an airlift overflow drain system, and slurry feed. Duratek uses thick ceramic refractories in glass contact areas that run hot and do not form a frozen glass skull layer. Air or inert gas bubbling is used to enhance melt convection, mixing, and melt rates. Duratek proposes to use 67 tonne/day capacity full-scale melters for the LLW vitrification facility. Duratek performed testing in its DuraMelter-100[3] (DM-100) and DuraMelter-1000 (DM-1000) melters at Vitreous State Laboratory of the Catholic University of America (VSL-CUA) in Washington, D.C. The DM-100 melter is a small unit rated at 0.1 tonne/day glass while the DM-1000 melter is a larger pilot-scale melter conservatively rated at 1.0 tonne/day glass. Both melters were operated during Phase 1 testing at steady-state processing rates approximately twice the rated 0.1 and 1.0 tonne/day capacities. A steady-state glass melt rate of ~67 kg/m^2/h was achieved in the DM-1000 test with slurry feed. Except for a cold-cap bridging occurrence during the DM-100 test, and the need to remove accumulated offgas duct deposits during both tests, several days of testing in both melters went smoothly and were relatively uneventful.

Penberthy Electromelt International, Inc. (PEI) of Seattle, Washington, demonstrated a high-temperature Joule-heated melter with sidewall molybdenum electrodes. PEI uses thick ceramic refractories in glass contact areas and does not rely on the formation of a protective frozen skull layer. The PEI melter feed system mixes the liquid LLW with absorbent glass-former additives

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[1]Unison is a trademark of Hosokawa Bepex Corporation.

[2]Inconel is a trademark of INCO Alloys International, Inc.

[3]DuraMelter is a trademark of GTS Duratek, Inc.

in screw chargers that deliver a moist granular solid feed directly to the melter. Multiple chargers with multiple drop points are used to maintain full batch blanket coverage and suppress volatile component losses. The mix-in-the-charger feed system is less complicated than preparing radioactive dry or calcined feeds and avoids mixing and slurry rheology issues associated with slurry feed, but requires accurate metering of dry glass-former and liquid LLW feed streams to control product composition. The PEI test melter had a 0.5-m^2 melt area with an estimated capacity of ~1 tonne/day of glass, and had three electrically heated drains in a lower sidewall for glass discharge. PEI proposes to use melters in the 25 to 50 tonne/day of glass capacity range for the full-scale LLW vitrification facility. Melter drain failures caused termination of Phase 1 testing before all testing objectives were met. However, PEI did achieve ~10 hours of operation with the mix-in-the-charger feed system.

U.S. Bureau of Mines (USBM) demonstrated a carbon electrode melter at the USBM Albany Research Center in Albany, Oregon, using prereacted granular dried feeds. Arc heating at the melt surface from vertical top-entering carbon electrodes is the primary heating mode. An increased component of Joule heating can be achieved using larger submerged electrodes and lower voltage. The USBM developed two dry feed preparation processes in which the NO_3^- and NO_2^- in LLW simulant were mostly destroyed by reaction with sugar and powdered carbon reductant additives during feed drying. Denitration in the USBM feed drying processes was more effective than in the Bepex spray-drying procedure used by Envitco. The USBM has proposed the use of 100 tonne/day glass capacity carbon electrode melters for the full-scale LLW vitrification facility. Glass melt rates ranged from 140 to 365 kg/m^2/h depending on electrode configuration and operating parameters. During its first demonstration run, USBM produced 4.7 tonne of glass over a 24-hour period. However, excessively high melting temperatures during the first run resulted in high volatile component losses. The USBM modified the melter drain and used larger-diameter submerged electrodes and lower voltage in two later demonstration runs to reduce maximum melt temperatures and volatility losses. Although significant reductions in volatile component losses were achieved, losses were still greater than demonstrated with cold-top Joule-heated melter technologies. With an improved drain design and larger submerged carbon electrodes, it may be possible to operate the melter in a full batch coverage cold-top mode with primarily Joule heating to further suppress volatile component losses. Later testing by USBM with coated electrodes also suggested that it may be possible to operate the melter with damp unreacted feeds.

Vectra Technologies, Inc. (Vectra) demonstrated its Ve-Skull* high-temperature Joule-heated melter with fully calcined, dried, and slurry feeds. The Ve-Skull melter is a double-shelled cylindrical pressure vessel with cooling water circulated between the outer and inner shell. The melter uses top-entering vertical molybdenum rod electrodes and a bottom drain. The inner shell of the test melter was refractory lined. Vectra will use either a thin refractory lining or no refractory lining in glass contact areas of the full-scale LLW vitrification facility melters and rely on a frozen glass skull layer which Vectra believes will provide extended melter life. The test melter had an effective melt area of ~0.6 m^2 and demonstrated a glass melting

*Ve-Skull is a trademark of Vectra Technologies, Inc.

capacity of ~0.8 tonne/day with slurry feed. Glass melt rates ranged from 43 to 68 kg/m^2/h depending on feed type. Vectra proposes to use 50 tonne/day slurry-fed full-scale melters of similar design for the LLW vitrification facility. The melter operated for 31 days during Phase 1 testing and produced a total of ~10 tonne of glass. About 0.5 tonne of calcined feed were prepared in a pilot-scale fluid bed calciner by Procedyne Corporation and melted during the dry feed melter demonstration. Preparation of significant quantities of dry feed using the 'rotary volume reduction' (RVR) drying process was unsuccessful. Much of the dry feed operation was conducted with cullet, carbonate batch, or 'V-Sim' simulated calcined feed.

Westinghouse Science and Technology Center (WSTC) of Pittsburgh, Pennsylvania, demonstrated a plasma torch-fired cupola furnace at its Waltz Mill Plasma Center. The test cupola furnace was fired by a single Westinghouse Electric Corporation (Westinghouse) Marc 11* plasma torch with a typical output power of 700 to 1400 kWe. The WSTC fed powdered frit glass-former additive and liquid LLW simulant as separate streams to a slurry pump where they were mixed and fed as a slurry to the furnace tuyere between the plasma torch and the melt crucible at the bottom of the cupola. This process produced ~7 tonne of glass during the 24-hour demonstration run. An evaluation of melter mass balance for this run was complicated because sample analyses data indicated that the LLW simulant to frit feed rates may have varied with time. However, data from individual 'snapshot' glass and feed analyses suggest that high volatile component losses likely occurred during the demonstration test.

Engineering studies initiated concurrent with Phase 1 testing included process flowsheet studies; design and facility configuration studies; safety and environmental assessments; and a remotability, operability, and maintainability evaluation. Volatile component and entrainment losses to the offgas were evaluated based on periodic feed, glass, and offgas samples analyses. Lowest volatile component and entrainment losses occurred with cold-top Joule-heated technologies with the least losses occurring in the Envitco test with dry feed and full batch blanket coverage. Following the Joule-heated technologies, in order of increasing volatility and entrainment losses measured during Phase 1 testing, were USBM, WSTC, and B&W, respectively.

Melt rates in Joule-heated melters with slurry feed were equal to, and in some cases greater than, melt rates achieved with dry feed. This is likely due to the high oxide loadings in excess of 1,000 g/L obtained when mixing glass-former materials with liquid LLW simulant concentrated to 10*M* Na. The fluxing action of molten Na salts in the early stages of melting is also likely beneficial. Glass melt rates with slurry feed demonstrated by Duratek and Vectra were in the 60 to 68 kg/m^2/h range. Glass melt rates measured with dry feeds ranged from a low of 43 kg/m^2/h with the fully calcined by Vectra feed to 62 kg/m^2/h with Vectra simulated calcine. Envitco demonstrated a glass melt rate of ~110 kg/m^2/h with dry feed, and correcting for incomplete cold-cap coverage, appeared to achieve a similar melt rate with slurry feed. Higher dry feed glass melt rates ranging from 140 to 365 kg/m^2/h were

*Marc 11 is a trademark of Westinghouse Electric Corporation.

demonstrated by the USBM carbon electrode melter. Glass melt rate in the WSTC plasma melter was ~300 kg/h with a crucible surface area of ~1 m^2.

Product glass samples were characterized for composition, redox, homogeneity, and durability. All vendor glass samples were sufficiently well reacted to meet the <1 g/m^2/day Na release product consistency test (PCT) durability requirement for Phase 1 glass formulations. However, product glass homogeneity results were variable, with the B&W test producing the least homogeneous product. Product glass compositions for some vendors varied significantly from the vendor's target glass composition. Uncertainties in the LLW simulant composition appear to be a partial cause for variations from target glass compositions. In some cases, volatility and entrainment losses were also significant factors in the variations from target glass compositions.

An Evaluation Board supported by an Advisory Panel of experts was assembled to review the melter technologies, Phase 1 test results, and vendor Phase 2 proposals, and to provide recommendations for Phase 2 testing. The Evaluation Board's conclusions are summarized as follows.

- Phase 1 testing provided sufficient information to support evaluation of the technologies and provided a majority of the essential technical information required for technology selection by June 1996.
- Joule-heated technologies were most highly rated, primarily based on the maturity of the technology for application to LLW vitrification, and superior melter mass balance results (low volatility and entrainment losses).
- The carbon electrode melter technology (USBM) shows sufficient promise to warrant additional evaluation.
- Cyclone combustion and plasma torch vitrification technologies are too immature to be considered as technology candidates within the Tri-Party Agreement schedule for LLW vitrification. Feed component volatility and entrainment, and the resulting recycle and process control requirements, also were key considerations.
- Slurry feeding (or moist mix-in-the-charger feed system) is preferred for reducing in-cell equipment complexity. The benefits of reduced feed processing complexity likely outweigh better melter mass balance results provided by dry feed processes, and the melt rate penalty associated with slurry or damp feeding appears to be small.

The Evaluation Board's recommendations for Phase 2 testing objectives included the following.

- Evaluate, under radioactive conditions, the volatility behavior of Tc and Cs, and assess Re as a possible nonradioactive surrogate for Tc.

- Confirm that volatile components can be recycled from the offgas into the feed without excessive buildup and that control of the glass composition with recycle can be achieved.
- Demonstrate cold-cap (or batch blanket) control and resistance to upsets such as reboil in Joule-heated melters.
- Investigate feed reductant additives to minimize loss of volatiles (particularly NO_x and Tc/Re) to the offgas system and improve electrode life.
- Investigate the relationship between melt rate and volatility.
- Demonstrate the effectiveness of skull operation for extending melter life.
- Determine if moist unreacted feeds are compatible with the USBM carbon electrode melter.
- Evaluate a less complex feed preparation process for moist unreacted feeds.
- Evaluate carbon versus molybdenum electrodes for high-temperature Joule heating.

2.0 BACKGROUND

This section provides background information and an overall description of the TWRS LLW Melter Vendor Testing Program. The Tri-Party Agreement and LLW vitrification requirements and assumptions described relate to the TWRS program baseline during FYs 1994 and 1995. These requirements and assumptions may be subject to renegotiation or change as a result of the FY 1996 TWRS Privatization Initiative.

2.1 TRI-PARTY AGREEMENT

A revised plan and schedule for disposal of Hanford Site tank wastes were agreed to in September 1993 (and finalized in January 1994) by the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), and the Washington State Department of Ecology during renegotiation of the *Hanford Federal Facility Agreement and Consent Order*, also known as the Tri-Party Agreement (Ecology et al. 1994). In the revised agreement, LLW and high-level waste (HLW) streams generated during retrieval and pretreatment would be vitrified. The Hanford Waste Vitrification Plant for HLW would be delayed and LLW vitrification would be initiated as the first priority. The following Tri-Party Agreement milestones were established for LLW vitrification activities.

- Begin LLW melter testing with simulants (September 1994).
- Complete melter feasibility and system operability tests, select reference melter(s), and establish reference LLW glass formulation that meets complete systems requirements (June 1996).
- Submit conceptual design and initiate definitive design of the LLW vitrification facility (November 1996).
- Initiate construction of the LLW vitrification facility (December 1997).
- Complete construction of the LLW vitrification facility (December 2003).
- Initiate hot operations of the LLW vitrification facility (June 2005).
- Complete vitrification of Hanford Site low-level tank waste (December 2028).

In the proposed waste processing scenario affective in 1994, the waste is retrieved from underground tanks and separated into a large-volume, liquid, LLW stream from which significant radionuclide removal has occurred, and a smaller volume HLW stream (sludge) in which most of the radioactivity will be concentrated. The resulting LLW and HLW streams are to be vitrified. Additional assumptions used to develop the planning case for LLW vitrification included the following.

- The LLW would be disposed of onsite, near the surface as glass.
- The LLW vitrification facility would have minimal radiation shielding, predicated on removal of Cs and Sr from the waste during pretreatment. (It was later determined that contact maintenance would likely not be possible.)
- The LLW vitrification facility would contain a minimum of two parallel lines to be constructed and started in a phased manner.
- The LLW vitrification facility would use standard glass industry high-throughput melters.
- Hot startup of the LLW vitrification facility would be in 2005 using pretreated double-shell slurry feed (DSSF) as initial feed.
- An eventual plant capacity of 200 ton/day glass was estimated to be required to complete LLW vitrification by 2018.

2.2 LLW MELTER VENDOR TESTING PROGRAM

A two-phase Melter Vendor Testing Program to be conducted with commercial vendors was initiated by WHC to comply with the Tri-Party Agreement fourth amendment requirements to begin melter testing by September 1994 and select a reference melter technology by June 1996. Phase 1 was a 'proof of principle' test. Phase 1 testing provided data to support an initial technology down-selection and an opportunity for vendors to become familiar with Hanford Site LLW vitrification issues and requirements. Phase 2 testing would incorporate improvements based on lessons learned during Phase 1 and provide more definitive data to support reference melter technology selection.

Phase 1 testing with the seven vendors, preliminary technology evaluation, down-selection, and recommendations for Phase 2 testing were completed during FYs 1994 and 1995. Three of the initially awarded vendors (B&W, Duratek, and Envitco) completed significant testing activities to process WHC-supplied LLW simulant before the end of September 1994. Based on early testing activities by these three vendors, the September 1994 Tri-Party Agreement milestone to begin LLW melter testing with simulants was met.

2.2.1 Objectives

The primary objective of the Melter Vendor Testing Program was to provide data to support selection of reference technologies for Hanford Site LLW vitrification by the June 1996 Tri-Party Agreement milestone date. The plan was to select technologies, but not vendors for those technologies. Vendors for the selected technologies would be selected through later procurements during plant design and construction activities.

Detailed technical objectives are defined in WHC-SD-WM-RD-044, *Evaluation of Melter System Technologies for Vitrification of High-Sodium Content Low-Level Radioactive Liquid Wastes* (SOW) (Wilson 1994). The primary technical objectives were to evaluate melter feed preparation processes and melter

performance. The performance of the vendors' offgas treatment system was not a primary concern because it was assumed that the Architect-Engineer would later design offgas and secondary waste treatment systems to meet nuclear facility requirements for the effluent streams to be treated. However, characterization of the melter offgas and other secondary process streams requiring treatment, and evaluation of the feasibility of treating these effluent streams, were primary technical objectives. Specific technical objectives included the following.

- Evaluate melter feed preparation options for LLW.
- Evaluate processing throughput and operation efficiency.
- Characterize process offgas and other effluent streams.
- Evaluate melter mass balance for volatile feed components including Na, B, Cs, Tc (Mo or Re surrogate), Cl, F, I, P, and S.
- Determine processing limits for LLW 'minor components' PO_4, SO_4, Cl, F, and Cr.
- Evaluate process control and product quality.
- Obtain information to support engineering studies, conceptual design, life-cycle cost estimates, and technology evaluation.
- Determine ability to idle the melter for extended periods, or shut down and restart, and the consequences of idling (including waste component volatility) and/or shutdown and restart cycles.
- Evaluate remotability, operability, and maintainability.
- Evaluate life expectancy, reliability, and maintenance requirements for melter and feed system equipment.
- Evaluate scaleup from systems tested (1 to 10 ton/day) to 50 to 100 ton/day.

2.2.2 Key Program Features

The demonstration tests were to be conducted by vendors in their facilities. Westinghouse Hanford Company supplied pre-mixed nonradioactive LLW simulant to each vendor for testing. The simulant was formulated to simulate the key chemical characteristics expected for a typical Hanford Site liquid LLW stream concentrated to 10*M* Na. Approximately 41,600 L of LLW simulant were made up in two lots for Phase 1 testing. The simulant lots were analyzed and confirmed to be within specified formulation limits before shipment to the vendors. The LLW simulant is described in Section 3.0.

Glass formulation was a vendor option. The SOW placed two requirements on glass formulation: (1) the waste loading (portion of the glass derived from the LLW simulant) shall be ~25 wt%, and (2) the normalized Na release rate measured by the PCT method at 90 °C shall be <1 g/m^2/day. Five

preapproved glass formulations developed by Pacific Northwest National Laboratory (PNNL) were offered. The vendors could choose one of the five PNNL glasses or formulate their own glass for testing. Vendor-formulated glasses were tested by PNNL for approval. Technical support was available to vendors through PNNL and the Savannah River Technology Center (SRTC). Three vendors chose to use one of the preapproved PNNL glasses for testing, three vendors chose to develop their own glass formulations, and one vendor chose to use a SRTC-developed glass formulation.

Independent laboratories were selected to perform sample analyses for the LLW Melter Vendor Testing Program. Analyses of glass, feed materials, other solids samples, and PCT durability measurements were performed by Corning Laboratory Services, of Corning, New York; and by the U.S. Geological Survey, Branch of Geochemistry, Analytical Chemistry Services Group, in Denver, Colorado. Liquid LLW simulants, offgas scrub solutions, and other liquid samples were analyzed by Quanterra Environmental Services of St. Louis, Missouri. Backup and confirmatory analyses on selected samples also were performed by PNNL. These laboratories were contracted directly by WHC.

Offgas measurements, including entrained particulate analyses and continuous emissions monitoring (CEM) for selected offgas components such as NO_x and SO_x, were conducted by qualified air quality laboratories using established EPA methods. Qualified laboratories providing offgas measurements were contracted by the melter test vendors. Various additional test monitoring measurements, such as material flow rates and temperatures, also were monitored by the vendors.

Westinghouse Hanford Company developed a test sample identification and chain-of-custody system that was used by all the test vendors. Test samples, including feed materials, glass, offgas scrubber solutions, and miscellaneous deposits and residues, were analyzed by independent laboratories contracted by WHC. Analytical results were entered into a WHC online electronic database (Mast 1995).

External technical consultants with commercial glass industry expertise assisted in proposal evaluation and review of vendor test plans. The consultants also observed vendor test activities, supported technical evaluations, and participated in Phase 2 down-selection. Similar technical support also was provided by PNNL and SRTC staff.

Engineering studies and supporting technology evaluations, and incoming test results evaluations, were initiated at WHC concurrent with Phase 1 testing. Engineering studies and evaluation activities included the following:

- Process flowsheet studies (WHC)
- Facility configuration and cost studies (Fluor Daniel, Inc. [Fluor])
- Design evaluation (WHC; Fluor)
- Remotability, operability, maintainability evaluation (WHC)
- Melter mass balance results (WHC, PNNL)
- Product (glass) quality results (WHC, PNNL)
- Safety assessment (Fluor)
- Environmental assessment (WHC)
- Quality assurance (WHC).

2.2.3 Documentation

Each vendor prepared a project-specific quality assurance plan and a test plan to be approved by WHC before conducting actual melter testing operations. Following testing, vendors prepared preliminary and full reports on Phase 1 test results. Each vendor also prepared a technical information report that described the full-scale melter system technology concept proposed for implementation in the Hanford Site LLW vitrification facility. In addition, each vendor prepared a report that provided available information on the expected life and reliability of the proposed equipment. Other than generic technology descriptions, a substantial amount of the vendor technical information and design details was classified as vendor proprietary and was not released. Westinghouse Hanford Company issued vendor test plans and final test reports for public release, and three vendors released technical information reports. Results of various engineering studies and evaluations performed in support of Phase 1 testing were released as WHC reports. This report provides a summary of results and released information from the Phase 1 LLW Melter Vendor Testing Program.

2.3 PHASE 1 VENDOR SELECTION

Westinghouse Hanford Company issued a request for proposal for the LLW melter vendor tests on February 25, 1994. Time constraints imposed by Tri-Party Agreement milestones for design, construction, and operation mandated that only relatively mature technologies requiring minimal additional development be seriously considered. In May 1994, a source Evaluation Board selected 7 vendors from 16 proposals. The following seven vendors and technologies were selected for Phase 1 demonstration testing:

- B&W, Alliance Research Center, Alliance, Ohio--Cyclone combustion melter, slurry feed
- Envitco, Toledo, Ohio--High-temperature Joule-heated melter, molybdenum electrodes, feed to be determined
- Duratek, Columbia, Maryland--Low-temperature Joule-heated melter, Inconel electrodes, slurry feed
- PEI, Seattle, Washington--High-temperature Joule-heated melter, sidewall molybdenum electrodes, moist mix-in-the-charger feed system
- USBM, Albany Research Center, Albany, Oregon--Carbon electrode melter, prereacted dry feed
- Vectra, Richland, Washington--High-temperature Joule-heated melter, top-entry molybdenum electrodes, calcined, dried or slurry feed
- WSTC, Pittsburgh, Pennsylvania--Plasma torch-fired cupola furnace, slurry feed.

Contract awards were delayed due to a bid protest. However, approvals were granted by the DOE to award some of the contracts while awaiting the outcome of a U.S. Government Accounting Office decision on the bid protest

before awarding the last vendor contracts. Letter awards were issued on July 26, 1994, to B&W, Envitco, PEI, and USBM to begin Phase 1 testing activities. During the following weeks, approval also was received to proceed with awards to Duratek and WSTC. On October 18, 1994, the U.S. Government Accounting Office denied the bid protest on all claims, thus allowing the final award to Vectra. The last Phase 1 melter testing operations were completed by Vectra in April 1995.

2.4 EVALUATION AND PHASE 2 SELECTION

Vendor contracts were to be extended to include Phase 2 testing as a WHC-exercised option. A technical Evaluation Board was established to review the Phase 1 testing results and vendor Phase 2 proposals and to make recommendations for Phase 2 testing. The evaluation was conducted in May 1995 and recommendations were developed for Phase 2 testing. The Evaluation Board deliberations are summarized and resulting recommendations for Phase 2 testing are provided in Section 10.0.

2.5 IMPACT OF TWRS PRIVATIZATION

On May 19, 1995, during the Phase 1 Evaluation Board deliberations, the DOE directed Phase 2 testing be to placed on hold pending a decision on privatization of Hanford Site tank waste immobilization. The DOE further requested that the evaluation and Phase 2 testing recommendations be completed and WHC be ready to exercise Phase 2 award options should the DOE decide not to proceed with privatization. The Secretary of Energy authorized implementation of the privatization strategy on September 22, 1995. Phase 2 testing was canceled and the vendor contracts were allowed to expire on December 31, 1995. Documentation of the Phase 1 LLW Melter Vendor Testing Program was completed during FY 1996 in order to be available to privatization bidders.

The DOE issued a request for proposals for TWRS privatization (RL 1996) in February 1996. Responding bidders are not obligated to propose a vitrified LLW form or use any technology evaluated during the LLW Melter Vendor Testing Program described in this report. At the time of the current writing, negotiations are proceeding among the Tri-Party Agreement agencies to develop milestones for DOE's revised approach for treatment of Hanford Site tank wastes.

3.0 PHASE 1 DSSF LLW SIMULANT

This section describes the development of the nonradioactive LLW simulant used during Phase 1 melter vendor testing, the preparation of 41,600 L of LLW simulant for distribution to individual melter test vendors, and the characteristics of the simulant.

3.1 BACKGROUND

Defense wastes at the Hanford Site are contained in 28 double-shell tanks (DST) and 149 older single-shell tanks (SST) in the form of liquids, slurries, sludges, and salt cakes. A reference chemical flowsheet for treatment of the tank wastes (Orme 1994) was developed in compliance with the fourth amendment to the Tri-Party Agreement. This flowsheet includes retrieval by sluicing and pumping along with waste pretreatment operations that involve sludge washing and ion exchange to remove Cs from the LLW fraction before vitrification. The pretreatment process will separate the wastes into HLW and LLW fractions. The DST waste compositions and volumes are better characterized than those of the SST wastes, so the strategy is to retrieve and pretreat DST wastes first, followed by SST wastes.

Two LLW simulant recipes were developed for LLW melter vendor testing based on projected average compositions for two LLW types, designated DSSF and remaining inventory (RI). The DSSF simulant is representative of LLW derived from selected DSTs, while the RI simulant represents LLW derived primarily from SSTs. Processing of both wastes is assumed to follow the same reference chemical flowsheet. The basis for simulant selection, simulant compositions, chemical formulation sequences, and chemical and physical characteristics for both simulants is discussed in WHC-SD-WM-TI-624, *Waste Simulant Development for Evaluation of Low-Level Waste Melter System Technology* (Shade 1994). The DSSF simulant was chosen for Phase 1 testing. The DSSF simulant composition was also used in the development and confirmation testing of LLW glass formulations.

3.2 SIMULANT FORMULATION

According to flowsheet assumptions (Orme 1994), the nominal LLW stream is 5*M* Na at pretreatment but will be ~10*M* Na after the evaporation process. The projected nominal compositions of the DSSF and RI waste streams normalized to 5*M* Na are presented in Table A-1 of WHC-SD-WM-TI-624 (Shade 1994) and in the SOW (Wilson 1994). The DSSF composition was based on the weighted mean compositions of LLW in each of six DSTs and the weighted mean composition of dilute wastes in several DSTs but which will be concentrated in evaporator/crystallizer campaigns. Analyses of the six DSTs and the DST dilute waste are documented in WHC-SD-WM-TI-528, *Grout Treatment Facility Waste Feed Projections* (Hendrickson and Conner 1994). Two simulant recipes, one 6*M* Na and one 10*M* Na, were developed for the DSSF waste. The 10*M* Na recipe was selected for the LLW melter tests because it was the likely Na concentration following evaporation to be received by vitrification, and also was more convenient to transport and process.

The chemical components selected for use in formulating the DSSF and RI simulants were determined by a team of engineers and scientists experienced with Hanford Site wastes, simulant development, and vitrification. The components selected were based on measured waste compositions from tank sampling and analysis plus projected compositions of real LLW streams generated by flowsheet operations. Major components calculated to contribute >0.005 wt% calcined oxide composition of the LLW were first included in the simulant formulation. The minor components (<0.005% of calcined composition) were then evaluated and included if judged to have significant impacts on processing or disposal. Elements Cs, Sr, I, and Mo (Mo as a surrogate for Tc*) were included because of their radiological significance. The concentrations for Cs^{+}, Sr^{+2}, IO_3^{-}, and Mo^{+6} chosen to be added to the 6*M* Na simulant formulations were spiked to 0.01*M* to ensure there would be sufficient levels of these components to analyze in the glass if only 10% of each were incorporated into the glass. When the decision was made to produce the simulants for vendor testing at 10*M* Na, the concentration for these four components was proportionally increased to 0.017*M*. Many of the included components also have processability significance. For example, Cs, I, Cl, F, and Tc are potentially volatile during vitrification and PO_4, SO_4, Cl, F, and Cr are known to have low solubility limits in silicate glasses.

Chemical compounds consisting of readily soluble salts were selected to represent each chosen constituent of the simulants. A cation-anion balance was done on concentrations of these compounds representing the target values which required adjustment of the simulant composition to 6.0*M* Na. This composition was recalculated to 10*M* Na. The 6.0*M* and 10*M* Na simulant compositions are presented in WHC-SD-WM-TI-624 (Shade 1994). The final 10*M* Na DSSF simulant target concentrations and the concentrations of compounds used to make up the simulant are presented in Table 3-1. This 10*M* Na simulant was the basis for the recipe used to make the large volume of DSSF waste simulant for Phase 1 testing.

3.3 RECIPES FOR SIMULANTS

To minimize the amount of solid precipitates that can occur in chemically complex caustic solutions, and to prevent the decomposition and volatilization of nitrates and carbonate during mixing, the simulants were made by first making acidic and basic solutions, each containing part of the chemical constituents, then mixing the two solutions together. The acid solution contained compounds that are typically soluble in neutral to slightly acid solutions, including Al and Fe nitrates as well as the Na ethylenediaminetetraacetic (EDTA) as a representative of total organic carbon (TOC). The EDTA is a complexant and helps prevent Al and Fe hydroxides, which are difficult to redissolve, from precipitating when the acid solution is added to a base. The base solution included the hydroxides, phosphates, sulfates, carbonates, and nitrites. The strategy was to slowly add the acid solution to the base solution so excess hydroxide would form soluble $Al(OH)_4^{-}$ and similar soluble metal species to minimize metal hydroxide precipitation.

*Oxides of Re appear to more closely simulate the volatility behavior of Tc oxides over a range of oxidation states than do oxides of Mo; therefore, Re is being considered as the Tc surrogate in future LLW simulant formulations.

Table 3-1. Low-Level Waste Simulant for Double-Shell Slurry Feed Waste Based on an Average of Six Tanks Plus Dilutes Normalized to 10.0*M* Sodium.

Component	Target feed conc. (mol/L)	Compound	Formula weight	Required for simulant (mol)
Al^{+3}	1.02	$Al(NO_3)_3 \cdot 9H_2O$	375.14	1.02
Ca^{+2}	1.0E-03	$Ca(NO_3)_2 \cdot 4H_2O$	236.16	1.0E-03
Cr^{+3}	8.7E-03	$Cr(NO_3)_3 \cdot 9H_2O$	400.17	8.7E-03
Fe^{+3}	7.7E-04	$Fe(NO_3)_3 \cdot 9H_2O$	404.01	7.7E-04
K^{+}	0.50	KOH	56.10	0.50
Mg^{+2}	1.0E-03	$Mg(NO_3)_2 \cdot 6H_2O$	256.41	1.0E-03
Mn^{+2}	4.2E-04	$Mn(NO_3)_2$	178.94	4.2E-04
Mo^{+6} (Tc)	0.017	$Na_2MoO_4 \cdot H_2O$	241.95	0.017
Na^{+}	10.0	--	--	--
Sr^{+2}	0.017	$SrCl_2$	158.52	0.017
Cs^{+}	0.017	$CsNO_3$	194.91	0.017
PO_4^{-3}	0.043	$NaH_2PO_4 \cdot H_2O$	138.00	0.043
IO_3^{-}	0.017	$NaIO_3$	197.89	0.017
CO_3^{-2}	0.27	Na_2CO_3	106.00	0.27
Cl^{-}	0.16	NaCl	58.45	0.13
F^{-}	0.25	NaF	42.00	0.25
SO_4^{-2}	0.043	Na_2SO_4	142.06	0.043
NO_3^{-}	3.2	--	--	--
NO_2^{-}	1.7	$NaNO_2$	69.00	1.7
OH^{-}*	3.8	NaOH	40.00	6.7
TOC	1.4 (16 g/L)	Na_4EDTA, C10	416.20	0.14

*An excess of 2.9 mol of NaOH is included to neutralize acidic hydrolyzable metal salts of Al, Ca, Cr, Fe, Mg, Mn, and Sr.

EDTA = Ethylenediaminetetraacetic acid
TOC = Total organic carbon

Related to this approach was a desire to evaluate if the two separate solutions would be more stable and have less precipitates than the total mixed solution. This evaluation was required to determine if the simulant shipped to melter test vendors would be easier to use (have less sludge or caked precipitates) in large quantities as two solutions mixed at the test site or as one solution.

The following recipe describes the laboratory preparation of a 1-L batch of 10*M* DSSF simulant. The components were added to ~300 mL of deionized water in the order listed in Tables 3-2 and 3-3, which describe the acid and base solutions. The solutions/slurries were constantly agitated during the additions and were not heated. Final simulants were prepared by slowly adding the acid solution to the base solution to avoid excessive heating. After mixing, the mixture is made up to the 1 L by adding water. The simulant is then agitated until no more solids dissolve. This bulk mixture (solution with suspended and settled solids) should be near to the target 10*M* DSSF composition presented in Table 3-1.

3.4 LABORATORY-PREPARED SIMULANT CHARACTERISTICS

This section describes the results of selected physical property measurements on laboratory-prepared DSSF and RI simulant batches.

Table 3-2. Chemicals Required to Prepare the 'Acid' Solution for 10*M* Double-Shell Slurry Feed Simulant.

Compound	Formula weight	mol/L	g/batch
$Al(NO_3)_3 \cdot 9H_2O$	375.14	1.02	381.39
$Ca(NO_3)_2 \cdot 4H_2O$	236.16	0.00105	0.25
$Cr(NO_3)_3 \cdot 9H_2O$	400.17	0.00867	3.47
$Fe(NO_3)_3 \cdot 9H_2O$	404.01	0.000767	0.31
$Mg(NO_3)_2 \cdot 6H_2O$	256.41	0.00103	0.26
$Mn(NO_3)_2$ (50% soln)	178.94	0.000417	0.0746
$CsNO_3$	194.91	0.0167	3.25
$Na_2MoO_4 \cdot H_2O$	241.95	0.0167	4.03
$Na_4EDTA \cdot 2H_2O$	416.2	0.135	56.19

EDTA = Ethylenediaminetetraacetic acid

Table 3-3. Chemicals Required to Prepare the 'Base' Solution of 10*M* Double-Shell Slurry Feed Simulant.

Compound	Formula weight	mol/L	g/batch
$NaNO_2$	69	1.67	115.00
KOH	56.1	0.5	28.05
$SrCl_2 \cdot 6H_2O$	266.62	0.0167	4.44
$NaH_2PO_4 \cdot H_2O$	138	0.0433	5.98
$NaIO_3$	197.89	0.0167	3.30
Na_2CO_3	106	0.267	28.27
NaCl	58.45	0.127	7.40
NaF	42	0.25	10.50
Na_2SO_4	142.06	0.0433	6.16
NaOH (pellets)	40	6.67	266.67

3.4.1 Settled Solids

The amount of settled solids was measured by allowing the freshly prepared solutions to remain undisturbed in a graduated cylinder for more than 24 hours and estimating the total volume of precipitated solids. A summary of the estimated volume of settled solids is presented in Table 3-4. The base solutions for the 6*M* and 10*M* Na DSSF simulants contained fairly large amounts of gelatinous solids, but when mixed with the acid solutions, they redissolved so the total amount of solids in the final solution was reduced to <5 vol%. The settling rates of the solids were slow for the 6*M* and 10*M* Na DSSF simulants and required several hours for a clear supernate to develop. The RI simulant contained some light-colored undissolved solids that settled out rapidly and a finer, darker fraction that resembled the solids in the other two DSSF simulants.

Table 3-4. Estimated Volume Percent Settled Solids After 24 Hours at 55 °C for Acid and Base Solutions and at Room Temperature for the Mixtures.

Simulant	Acid	Base	Mixture
DSSF, 6*M* Na	<5	15	<3
DSSF, 10*M* Na	<5	50	<5
RI, 6*M* Na	10	5	10

DSSF = Double-shell slurry feed
RI = Remaining inventory

3.4.2 Resuspendability

An important property of slurries is the ability to resuspend the solids once they have settled. A qualitative evaluation of the 'resuspendability' of the solids in the three simulants was done by allowing the solids to settle in a Teflon* bottle for more than 24 hours and then slowly agitating them by turning the containers end-over-end several times, each time inspecting the bottom for the presence of remaining solids. The solids in the 6*M* and 10*M* Na DSSF simulants and the finer, dark solids in the RI simulant were resuspended during the first two rotations of the bottles. The lighter-colored solids in the RI sample appeared gelatinous and 'dripped' from the bottom when the bottle was inverted. After about five rotations of the bottle, all the solids were resuspended. Based on these observations, it appeared that the solids in all the simulants could be easily resuspended by moderate agitation.

3.4.3 Density

The densities of the solutions/slurries were measured by weighing a known volume within a graduated cylinder. The results are summarized in Table 3-5.

3.4.4 Viscosity

Viscosities of the mixtures were measured using a Haake rotary viscometer. The viscosities at room temperature (23 °C) are shown in Table 3-6.

3.4.5 Moisture Content

Samples of the simulants were dried at 120 °C in a vacuum oven for several days to determine weight loss (moisture content). The results are shown in Table 3-7.

Table 3-5. Densities of Simulated Wastes at Room Temperature (g/cc).

Simulant	'Acid'	'Base'	Mixture
DSSF, 6*M* Na	1.21	1.38	1.31
DSSF, 10*M* Na	1.39	1.58	1.42
RI, 6*M* Na	1.35	1.22	1.28

DSSF = Double-shell slurry feed
RI = Remaining inventory

*Teflon is a trademark of E.I. du Pont de Nemours & Company.

Table 3-6. Viscosity of Simulated Wastes at 23 °C.

Simulant	Viscosity (cP)
DSSF, 6*M* Na	3.6 ± 0.2
DSSF, 10*M* Na	11.1 ± 0.2
RI, 6*M* Na	2.6 ± 0.2

DSSF = Double-shell slurry feed
RI = Remaining inventory

Table 3-7. Moisture Content of Simulated Wastes (Determined by Drying at 120 °C).

Simulant	Moisture content (wt%)
DSSF, 6*M* Na	65
DSSF, 10*M* Na	50
RI, 6*M* Na	65

DSSF = Double-shell slurry feed
RI = Remaining inventory

3.5 CHARACTERISTICS OF PHASE 1 DSSF SIMULANT LOTS

Optima Chemicals, Inc. of Douglas, Georgia, was selected to manufacture ~41,600 L of 10*M* Na DSSF simulant according to the recipe described. This simulant was made in two lots, one ~26,500 L in August 1994 and the other ~15,100 L in October 1994. These lots are hereafter described as Lot 1 and Lot 2. Lot 1 was prepared as two batches (Optima Batches 1 and 2), which were mixed to make up Lot 1. Lot 2 was prepared as a single batch (Optima Batch 3). The simulant was shipped to melter test vendors in 55-gal (208-L) steel drums. Samples from both lots of these simulants were analyzed by PNNL in Richland, Washington, and by Quanterra Environmental Services of St. Louis, Missouri. The results of these analyses are summarized in Table 3-8. The density and percent settled solids for the two lots of DSSF simulant measured by PNNL, WHC 222-S, and Quanterra laboratories are presented in Table 3-9.

The Na concentration specification for the DSSF simulant was 10.0*M* ± 0.5*M*. Based on the density data, it was determined that the Quanterra value for Lot 1 Na was low; therefore, additional analyses were conducted at PNNL based on glasses batched from dry chemicals and from the DSSF simulant assuming 10.0*M* Na concentration. The PNNL LLW glass composition LD6-5510 was chosen because this composition was used by two of the vendors for Phase 1 testing. Samples of the standard LD6-5510 glass batched from dry chemicals and from the Optima Lot 1 DSSF simulant were dissolved following KOH fusion and analyzed side-by-side. This same procedure was later followed to confirm the analyses of the Lot 2 simulant. Results for Na and other selected components of interest are presented in Table 3-10. By ratio to the target 20.0 wt% Na_2O concentration, the results indicated a 9.65*M* Na for the Lot 1 simulant and a 10.5*M* Na for the Lot 2 simulant. Both lots were accepted for Phase 1 testing.

Table 3-8. Analytical Results from Double-Shell Slurry Feed Simulant Lots 1 and 2 Manufactured by Optima Chemicals, Inc.

Component	Target (mol/L)	Analytical results			
		Lot 1 PNNL	Lot 1 Quanterra	Lot 2 PNNL	Lot 2 Quanterra
Al^{+3}	1.02	0.96	0.95	1.15	1.31
Ca^{+2}	0.001	0.0025	0.0029	0.0090	0.0037
Cr^{+3}	0.0087	0.0062	0.0074	0.0100	0.0104
Fe^{+3}	0.00077	0.00072	0.00068	0.00130	0.00115
K^{+}	0.5	0.51	0.45	0.61	0.58
Mg^{+2}	0.001	0.0025	0.0031	0.0021	--
Mn^{+2}	0.00042	0.00047	0.00044	0.00064	0.00060
Mo^{+6}	0.017	0.018	0.016	0.020	0.022
Na^{+}	10.0	9.5	8.5	10.6	10.46
Sr^{+2}	0.017	0.016	0.013	0.018	0.015
Cs^{+}	0.017	0.015	0.020	0.017	0.027
PO_4^{-3}	0.043	0.036	0.038	0.039	0.036
IO_3^{-}	0.017	0.020	--	0.025	0.017
CO_3^{-2}	0.27	0.29	0.25	0.38	0.30
Cl^{-}	0.16	0.13	0.16	0.14	0.18
F^{-}	0.25	a	0.04	a	0.02
SO_4^{-2}	0.043	0.037	0.040	0.045	0.039
NO_3^{-}	3.1	3.03	2.95	3.05	2.34
NO_2^{-}	1.7	1.65	1.63	1.9	2.03
OH^{-}	3.8	3.04	b	3.75	b
TOC	1.4	1.45	1.46	1.65	0.87

[a]The PNNL did not report values for F^{-} because of the expected low solubility of NaF in concentrated Na^{+} solutions.

[b]The Quanterra method used for OH^{-} was not specific to the hydroxide ion and is not reported.

PNNL = Pacific Northwest National Laboratory
TOC = Total organic carbon

Table 3-9. Physical Properties of Double-Shell Slurry Feed Simulant.

Analysis	Development data (PNNL)	Lot 1 PNNL	Lot 1 WHC	Lot 2 PNNL	Lot 2 WHC	Lot 2 Quanterra
Density	1.42	1.45	1.43	1.50	1.39	1.522
% settled solids	<5	--	2.7	--	47	--
% centrifuged solids	--	--	1.5	--	22.2	--

PNNL = Pacific Northwest National Laboratory
WHC = Westinghouse Hanford Company

Table 3-10. Comparison of LD6-5510 Glass Made with Optima Chemicals, Inc. Double-Shell Slurry Feed Simulant Lots 1 and 2 and Dry Chemicals.

Oxide	LD6-5510 target composition	Lot 1 simulant glass	Dry chemical batched glass[a]	Lot 2 simulant glass	Dry chemical batched glass[b]
Al_2O_3	10.00	9.86	10.04	10.25	9.92
B_2O_3	5.00	5.03	5.17	4.88	5.08
CaO	5.00	5.48	6.27	4.98	5.12
Cr_2O_3	0.04	0.057	0.047	0.05	0.03
Fe_2O_3	0.004	0.089	0.098	0.05	0.15
MoO_3	0.15	0.182	0.142	0.17	0.12
Na_2O	20.00	19.069	19.768	21.33	20.16
P_2O_5	0.20	0.257	0.376	0.22	0.19
SO_3	0.22	0.276	0.227	0.21	0.22
SiO_2	56.78	55.992	55.523	51.65	53.75

[a]Standard LD6-5510 glass analyzed with Lot 1 glass sample.
[b]Standard LD6-5510 glass analyzed with Lot 2 glass sample.

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4.0 PHASE 1 MELTER DEMONSTRATION TESTS

Summaries of the Phase 1 LLW testing conducted by the seven vendors are provided in the following subsections. These subsections were drafted by the WHC cognizant engineer for each vendor and have been edited for this report.

4.1 ENVITCO

Envitco of Toledo, Ohio, provides melter technology specifically for waste and environmental vitrification. Toledo Engineering Company (TECO) of Toledo, Ohio, an established provider of engineering services to the commercial glass industry, is affiliated with, and provides melter design support to, Envitco. The actual Phase 1 testing was performed under subcontract through Envitco at Clemson University. The Phase 1 testing conducted by Envitco was performed under WHC contract MMI-SVV-384213.

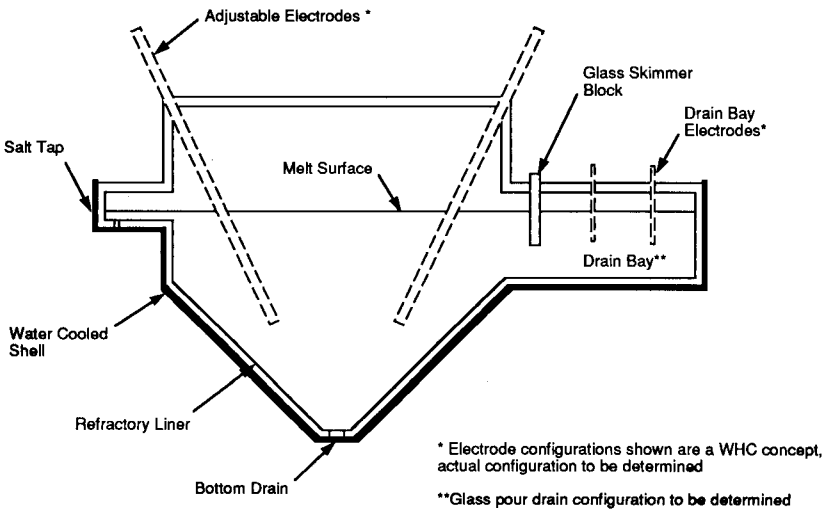
4.1.1 Melter Technology Description

The Envitco melter is a high-temperature Joule-heated melter that uses molybdenum rod electrodes. The melter uses relatively thin ceramic refractories enclosed in a water-cooled metal shell and relies on cooling of the refractories and formation of frozen glass skull on the inner refractory surfaces to provide extended refractory life.

4.1.1.1 Full-Scale Concept. Envitco proposed to use four melters, each capable of processing 50 tonne/day of glass, to meet the 1994 planning basis LLW vitrification facility capacity of 200 tonne/day. A conceptual design diagram for the proposed EV-50MT melter is shown in Figure 4-1. The main tank is heated by slanted top-entering molybdenum electrodes. Envitco has not yet released actual electrode configuration and design details for the main tank or drain bay electrodes. It is anticipated that the electrode geometry will be adjustable by extension or withdrawal of the electrodes through their protective sleeves or by changing their slant angle to allow optimization of power distribution and melt cell convective flow. Design of the electrode assemblies to be replaceable from above using the melter cell bridge crane is anticipated.

The melter has a side drain bay separated from the main melting tank by a water-cooled skimmer block replaceable from above. The drain bay area would also be heated by molybdenum electrodes. Envitco proposes to use mechanically controlled refractory metal drains mounted through the floor of the drain bay. Similar mechanically controlled drain systems have proven successful in smaller Envitco melters. Other drain alternatives, such as direct overflow weir discharge of the glass, are under consideration. The main melter tank has a sloped bottom with a bottom drain for removal of precipitated metals and sludges and for draining the tank if required. Bubbling is proposed as an option to provide additional melt convection and mixing. Salt taps mounted at the melt line would allow tapping off of any molten salt layers that may accumulate on top of the glass melt. The glass level is monitored by nuclear detectors mounted outside the drain bay.

Figure 4-1. Proposed Envitco, Inc. EV-50MT Full-Scale Melter Configuration.



Envitco initially proposed to use dry feeding if engineering of a remote dry feed preparation system is shown to be practical. Spray drying of blended melter slurry feed was demonstrated for Phase 1 testing, and testing with a dry feed similar to the Type B feed developed by the USBM for Phase 1 has been proposed by Envitco for Phase 2 testing. If dry feed preparation proves to be impractical for the LLW vitrification facility, the melter could be slurry fed. Slurry feed would be batched in a feed makeup tank and forwarded to a melter feed tank after analysis to verify its composition. Another option being considered is to use a moist mix-in-the-charger feed system. The mix-in-the-charger feed system, where liquid LLW is mixed with absorbent glass-former materials in a screw charger directly feeding the melter, is a simple approach that minimizes radioactive materials processing in front of the melter. However, the need to accurately and continuously meter two separate process streams to the feed chargers is viewed as a potential process control issue with the mix-in-the-charger feed system.

4.1.1.2 Technical Issues. The following technical issues need to be addressed to implement the Envitco melter concepts in the LLW vitrification facility.

Reboil/Melt Foaming--The potential for melt reboil or melt foaming upsets is an issue with all glass melters that contain a large pool of melting glass

when processing LLW feeds with potentially variable chemistry. Reboil or foaming upsets are usually caused by redox reactions in the glass melt that liberate gases such as O_2, CO, CO_2, and SO_2. The LLW feed characteristics, particularly the content of components such as transition metal oxide formers and sulphate that can participate gas producing melt redox reactions, and the correct use of feed reductant additives, are important considerations in preventing reboil/foaming upsets.

Batch Blanket Control--A glass industry consultant has expressed concern regarding the potential for batch blanket bridging operating with full cold-top dry batch coverage. 'Bridging' occurs if an impermeable layer occurs at the bottom of the batch crust across the melt pool from sidewall to sidewall. Trapping of gases under such a bridged crust may cause a void space preventing heat transfer from the melt to the batch crust. Bridging of the cold cap to the melter walls is also a potential issue with slurry feed. This did not appear to be a problem during the Envitco Phase 1 testing with dry or slurry feeds. However, crust control and avoidance of bridging will need to be verified with the final melter and feed system designs.

Electrodes--Envitco melters built to date have used sidewall molybdenum electrodes. Although top-entering molybdenum electrodes have been used in commercial melters, Envitco has not disclosed a detailed design for the proposed EV-50MT melter. It will be a challenge to incorporate design features to allow remote adjustment, maintenance, and replacement. Envitco would be supported by affiliates TECO and KTG Systems, Inc. in design of the electrode system. The LLW feeds will likely contain corrosive salt components such as Cl, F, SO_4, and PO_4, and also may contain trace reducible metal components such as Cu, Ni, and Sb that may potentially attack molybdenum electrodes. Extended testing of the top-entering electrodes with representative LLW feeds will be needed to verify the long-term electrode performance for the main and drain bay electrodes.

Melter Drains--There is some uncertainty yet in the drain design. A mechanically controlled drain of the design demonstrated on smaller Envitco melters can be expected to need periodic replacement or maintenance during the estimated melter life of 3 or more years with continuous pour rates of 50 tonne/day. Alternate pour drain designs, such as a simple overflow weir design, may be considered. Also, detection of accumulated metals and refractory or precipitated sludge at the bottom of the melter, and control of the bottom drain for removal of these materials, needs to be demonstrated.

Remote Operation and Maintenance--To different degrees, remote operation and maintenance issues exist with all the tested vendor technologies. For Envitco, issues to be addressed include adjustment and replacement of electrodes (main and drain bay); operation and maintenance of drains; operation of salt taps and handling as a secondary waste; monitoring of sludge/metals buildup; operation of bottom drain and handling drained material as secondary waste; and monitoring of batch blanket, crust control, and feed distribution (feed system is not yet defined). To extend melter life up to 10 years, Envitco proposes to patch melter wall hot spots with water-cooled panels, for which practical procedures have not been developed.

4.1.1.3 Technology Strengths. The following strengths are identified for the Envitco melter technology:

- Maturity of technology (molybdenum electrode Joule-heated melters in many configurations have been used in the commercial glass industry for more than 40 years)
- Low volatility and entrainment losses and high decontamination factors (DF) when operated in the cold-top mode
- Technical resources represented by Envitco and affiliated companies TECO (melter system design and engineering services); KTG Systems, Inc. (melter electrodes); and Dreicor (melter system fabrication).

4.1.2 Phase 1 Testing

A letter order to begin Phase 1 test planning was awarded to Envitco on July 26, 1994. Final revisions to the test plan were approved on September 29, 1994, and the document was subsequently issued for public release (WHC-SD-WM-VI-022 [Wilson 1995]). Dry melter feed was prepared by Hosokawa Bepex Corporation in Minneapolis, Minnesota, during September 20-23, 1994. The melter demonstration testing was conducted at Clemson University with vitrification of the Bepex dried feed occurring during the week of October 10, 1994; demonstration testing with slurry feed occurred the following week. A detailed Phase 1 test report was prepared by Envitco and Clemson University and subsequently issued for public release (WHC-SD-WM-VI-023 [Wilson 1996]).

4.1.2.1 Test Facilities. The Phase 1 testing was conducted in the Envitco EV-16 melter at Clemson Research Park in Anderson, South Carolina. Clemson University has established the Vitrification Research Center in cooperation with Westinghouse Savannah River Company and several industrial participants including Envitco.

The EV-16 is a small test melter with a throughput capacity that ranges from 0.5 to 1 tonne/day. The melt chamber has a square cross-section that is 0.45 m across (a 0.21-m^2 melt area) with a working depth of up to 0.4 m. The melter is heated by four horizontal molybdenum electrodes entering through the center of each sidewall operating on 2-phase power delivered through a Scott-T transformer. A proprietary mechanically controlled drain assembly penetrates vertically through the center of the melter bottom. A batch hopper and a screw charger are mounted behind the melter plenum on an X-Y motion platform to allow uniform distribution of dry batch material over the glass melt pool. Although the feed delivery and screw charger motion can be programmed for automated feeding, the charger batch drop position was manually controlled during Phase 1 testing.

4.1.2.2 Feed Preparation and Glass Formulation. Envitco selected the pre-approved PNNL LD4-912 borosilicate glass formulation for testing. The nominal glass composition is 20% Na_2O, 9% B_2O_3, and 12% Al_2O_3, and the balance is SiO_2 plus ~3.3% other minor components from the LLW simulant. An addition of 1% Fe_2O_3 to one dry feed batch ensured sufficient Fe for glass redox analysis and allowed monitoring of product glass composition response to a small step

change in feed composition. Alumina was batched as alumina trihydrate, boria as boric acid, and silica as a mixture of silica sand and precipitated silica. The sand-to-precipitated-silica ratio was adjusted to provide optimum slurry rheology (viscous enough to retard settling but not too viscous to pump) when mixed with the LLW simulant. The nominal batch formulation is presented in Table 4-1. Essentially the same slurry mix was prepared for spray drying to prepare the dry feed, and for direct feeding to the melter for the slurry feed portion of Phase 1 testing.

Fine powdered activated carbon was added as a reductant additive during slurry mixing. The quantity of carbon to be added was calculated based on the stoichiometric quantity needed to react with the NO_3^- and NO_2^- contained in the LLW simulant to produce $N_2 + CO_2 + H_2O$. The 4.04 g of carbon per 100 kg of glass that was used is 100% of the calculated stoichiometric requirement. A total of 110% of stoichiometric carbon addition was used in the initial feed drying runs (UN-1 through UN-4) and 100% stoichiometric carbon was added for the main production drying runs (UN-5 through UN-7).

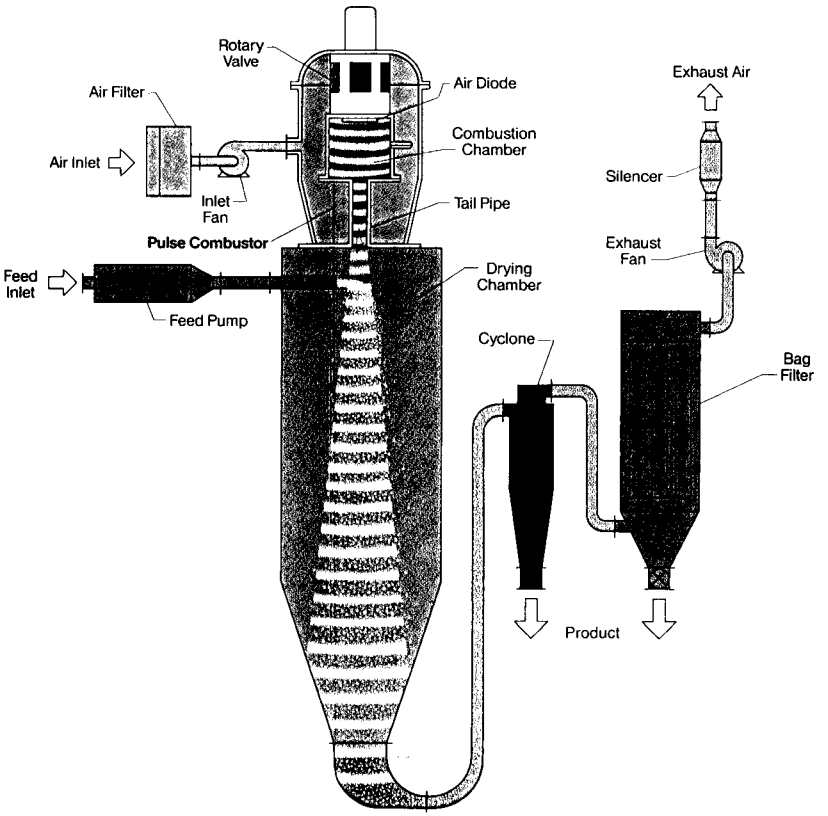
Dry feed was prepared during September 19-23, 1994, at Hosokawa Bepex Corporation, Minneapolis, Minnesota, using the Bepex Unison spray-drying process (Figure 4-2). Laboratory testing had indicated that the exothermic $C/NO_3^-/NO_2^-$ reactions initiated and proceeded readily when the temperature reached ~300 °C. Initial trial drying runs UN-1, UN-2, and UN-3 were made on a partial slurry without the silica sand which was to be mixed in after drying

Table 4-1. Batch Formulation.

Batch material	Weight (kg)	Oxide	Oxide weight (kg)	Weight in glass (kg)
Low-level waste simulant (1.43 kg/L)	92.25	Na_2O	20.00	20.00
		K_2O	1.52	1.52
		Al_2O_3	3.36	12.00
		Other	1.71	1.71
Alumina trihydrate	13.31	Al_2O_3	8.64	--
Boric acid	15.98	B_2O_3	9.00	9.00
Precipitated silica	11.08	SiO_2	10.04	55.77
Unimin[a] 5010 sand	45.82	SiO_2	45.73	--
Activated carbon	4.04[b]	--	--	--
Totals	182.48	--	100.00	100.00
Fe to Batch UN-6	--	Fe_2O_3	1.00	--

[a]Unimin is a trademark of Unimin Corporation.
[b]Carbon addition based on 100% stoichiometric requirement for denitration to $N_2 + CO_2 + H_2O$.

Figure 4-2. Hosokawa Bepex Corporation Unison Spray-Drying Process.



the partial slurry. Runs UN-4 through UN-7 were made on full batch slurry. Run UN-1 was run at 470 °C with the partial slurry and produced a sticky product that collected in the outlet duct causing early run termination. Runs UN-2, UN-3, and UN-4 were made at dryer outlet temperatures of 150, 250, and 205 °C, respectively. Water spray cooling was required before the bag filter when dryer outlet temperature was much above 205 °C to prevent the bag temperature limit of 200 °C from being exceeded. Production runs UN-5, UN-6, and UN-7 were run with full batch slurry with a dryer outlet temperature of 205 °C. One percent Fe_2O_3 was included in the UN-6 run batch. The UN-5 and UN-7 dried products were blended together in a ribbon blender to produce feed Lot UN-57.

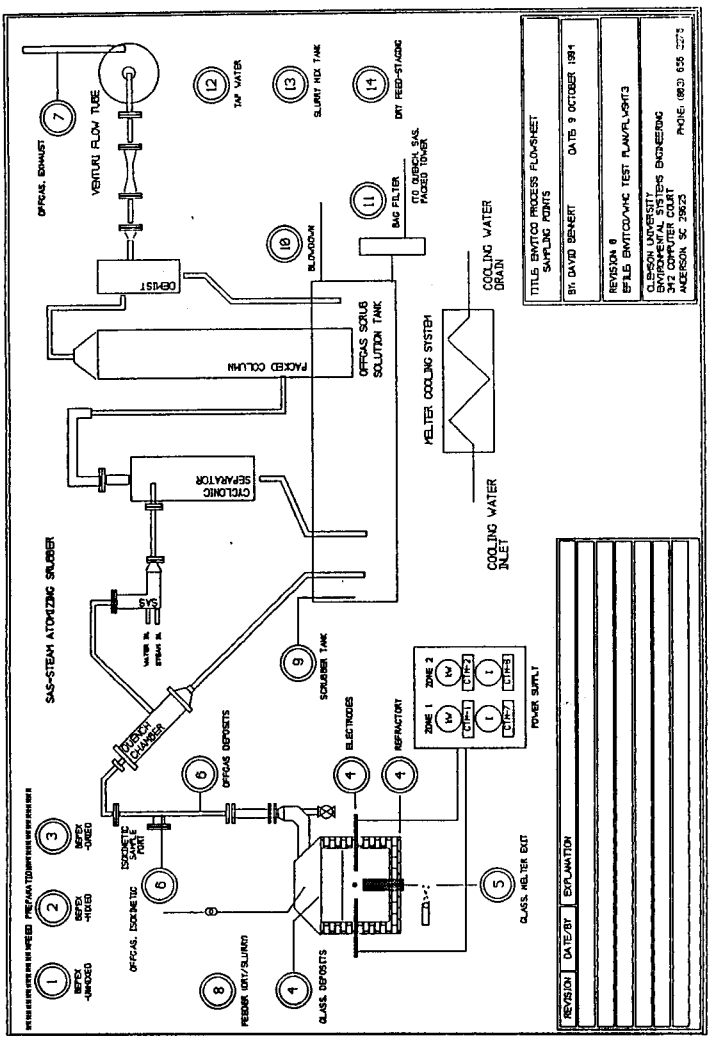
The spray-dried product was a fine powder that required compaction and granulation to produce a melter feed that would not be excessively dusty resulting in excessive offgas entrainment when fed to the melter. An initial small trial batch of dried material had been compacted by feeding the material through a roller compactor producing a 2-mm thick sheet that was granulated to produce a non-dusting free-flowing feed material. Because of the large quantity of material to be compacted from the production runs, a higher capacity compactor compacted the dried feed into bars (~2.5 cm diameter by 15 cm long). The compacted bars were crushed and screened to -5 mesh. The crushed and screened material was put in plastic bag-lined cardboard barrels for shipment to Clemson University.

4.1.2.3 Test Monitoring and Sampling. A schematic diagram of the EV-16 test melter system showing sampling points is presented in Figure 4-3. Glass samples (~500 g) were collected directly from the melter pour stream onto a steel plate at 4-hour intervals and set aside to cool. The offgas scrubber tank solution and the blowdown tank, which collected overflow from the offgas scrubber tank, also were sampled at 4-hour intervals. The blowdown tank volume was calibrated to depth, and after each sampling, the volume was recorded and the tank emptied. For soluble components, the blowdown solution concentrations times the volume collected for the interval were taken to equal the amount of that component scrubbed from the offgas during the interval. Solids scrubbed from the offgas were collected on a bag filter (5 μm). The bag filter was changed out three times during the test, dried filtered solids were weighed, and a sample was taken for analysis.

Trigon Engineering Consultants of Columbia, South Carolina, performed offgas measurements and analyses during the third and fourth days of the dry feed run. Isokinetic offgas samples were taken using EPA Method 29 for determination of metals and Method 26A for determination of hydrogen halides and halogens. A white fume coming off the glass pour stream also was sampled by placing pipe sections around the pour stream below the melter drain outlet and pulling an air/fume sample through the Method 29 sampling train. Continuous emissions monitoring measurements were made for NO_x, SO_x, CO_2, CO, and O_2 during testing with dry feed.

A microcomputer data logging system recorded various temperatures, flows, and other operating parameters. The glass temperature in the melter was monitored by a thermocouple inserted through the center of an electrode to the knob at the electrode hot end. The glass pour stream temperature was

Figure 4-3. Envitco, Inc. EV-16 Test Melter Flow Diagram Showing Test Sampling Points.



monitored by an optical pyrometer. Voltage and current were monitored on both electrode circuits. Timed glass samples were periodically taken between the main glass samples and weighed to determine melter pull rates.

Following the dry and slurry feed demonstration tests, the melter was disassembled and inspected, and samples were taken of various residues and accumulated deposits. The electrodes were removed, weighed, measured, and photographed. Refractories were examined in detail.

4.1.2.4 Test Chronology. Before the Hanford Site demonstration test, the EV-16 melter was rebuilt with new electrodes, refractories, and drain assembly.

October 7, 1994--The melter was started on Friday, October 7, with a pre-melted frit manufactured to the PNNL LD4-912 glass composition, and idled hot over the weekend.

October 10, 1994--Feed charging with the Bepex NU-57 feed lot began at 1100* with an initial target glass pull rate of 13.6 kg/h (30 lb/h). Excessive dusting of the dry feed and offgas entrainment were noted as the feed dropped ~20 cm from the feed charger onto the batch blanket. The problem was that the bar compaction and granulation process used at Bepex for this feed did not adequately compact the as-dried powder feed.

October 11, 1994--Melting of Bepex UN-57 feed continued with a nominal glass pull rate of 13.6 kg/h to bring the melter to compositional steady state with this feed. Tests were performed adding various amounts of water to suppress dusting and it was decided to add 7 wt% water. The water was added while tumbling the dry feed in a cement mixer before adding the feed to the melter screw charger feed hopper. The water addition successfully suppressed the dusting and offgas entrainment. The 7% wetted feed was used during the day shifts on October 12 and 13 when offgas measurements were being made.

October 12, 1994--Power and feed rates were increased during the early morning to obtain a glass pull rate of 22.7 kg/h (50 lb/h). Two Method 29 samples, two Method 26A samples, and three gaseous emissions measurements were completed (all 1 hour each). Feed Lot UN-57 was finished at ~1500, feed Lot UN-6 (1% Fe_2O_3) was started, and glass sampling frequency was increased to one sample every hour during the next 6 hours, followed by glass sampling every 2 hours during the next 20 hours. At 2000, the power and feed rates were reduced to pull 16 kg/h to conserve feed. The total inventory of feed Lot UN-57 and UN-6 was 1,643 kg, and it was desired to run October 13 on the remaining UN-6 feed at 22.7 kg/h when continued offgas and melter mass balance data were to be taken the next day.

October 13, 1994--The power and feed rate were increased during the morning to obtain a glass pull rate of 22.7 kg/h. Two Method 29 samples, two Method 26A samples, and two gaseous emissions measurements were made (all 1 hour each). An additional non-isokinetic sampling for multiple metal emissions was conducted to sample the white fume coming off the glass pour

*Military time is used for test chronology discussion throughout this report.

stream. At ~2100, feed Lot UN-6 was finished and feeding of uncompacted feed produced in Bepex trial Runs UN-1 through UN-4 was started. All critical test measurements for the dry feed demonstration had been completed and it was desired to melt the feed drying trial lot material to dispose of it.

October 14, 1994--By 1530 on Friday, October 14, some indications of melt foaming were observed and power was reduced to maintain batch cover. Batch charging was stopped and by 1830 the foaming had become severe and the glass level had increased significantly. Power was further reduced and any increase in power was seen to immediately aggravate the foaming. The melter was maintained in a hot-hold condition at 15-kW power during the weekend to allow outgassing to occur.

October 16, 1994--A low-flow sensor trip in one of the water-cooling zones caused automatic shutdown.

Week of October 17, 1994--The melter was restarted on October 17 and the foaming again started. The melter was maintained in a hot-hold condition and any attempt to increase power again resulted in aggravated foaming. However, the foaming tendency was tending to decrease through October 18. During the evening of October 18, the melter was again automatically shut down by the same low-flow sensor. The melter was restarted and at 1513 on October 19, power was successfully increased and slurry feeding was started. Slurry feeding continued through October 21 with periods of varied feed rates and some periods of hot hold.

4.1.3 Results and Observations

Melter operations went smoothly as planned with two exceptions: the melt foaming event at the end of the dry feed run, and the two low-cooling flow trips that shut down the melter during the several days of the hot-hold period while outgassing the glass melt.

4.1.3.1 Melt Rates. During the first 2 days of dry feed testing, the average glass melt rate was ~14 kg/h (~67 kg/m^2/h) and the melt temperature as measured by electrode thermocouple was ~1350 °C. Power was increased to achieve a target steady-state glass melt rate of ~23 kg/h (~110 kg/m^2/h) during the day when offgas measurements were to be made on October 12 and October 13. The 7% wetted feed was used during these higher melt rate periods. Peak glass pull rate was ~26.4 kg/h with a corresponding electrode thermocouple temperature of 1500 °C. During the afternoon of October 12, the glass pull rate was held steady at ~20 kg/h with an electrode thermocouple temperature of ~1420 °C.

During slurry feeding demonstration, with a single feed nozzle near the back of the melter, slurry cold-cap coverage was an issue. Only 30% coverage was initially obtained. An insulating board was placed over the front portion of the melt surface in the front to reduce heat loss and this allowed up to 60% cold-cap coverage to be achieved. Under these conditions, the melt rate is estimated to be ~14 kg/h glass, or ~110 kg/m^2/h adjusted for 60% cold-cap coverage. However, because of variations in feed rates and glass pull rates, and intermittent periods when feeding was stopped, the actual melt rates achieved with slurry feeding are somewhat uncertain. The melt rate was

limited by power (500 A limit), and while the feed rate was increased from an equivalent glass production rate of 14 to 22.5 kg/h at maximum power, the electrode thermocouple temperature decreased from ~1340 °C to ~1200 °C.

4.1.3.2 Assessment of Feed Preparation. The low denitration efficiencies achieved (~20%) with the Bepex spray-drying process were an issue. Increasing the drying temperature appeared to increase the tendency for the dried powder to stick and accumulate in the outlet duct and in the dryer, possibly due to the presence of molten salt phases. Another issue was the need to compact the dry powder produced to minimize dusting in the melter. The dry powder handling, compaction, and granulation processes require complex mechanical equipment that would be difficult to operate and maintain in a remote shielded facility. Because of these issues, Envitco is considering the USBM Type B (using a belt dryer) feed preparation methods for Phase 2 testing. Another alternative requiring less complex equipment is to mix the LLW and glass formers in a screw charger and directly feed this mixture to the melter. An advantage of the dry feed is that it can be distributed to form a complete coverage dry batch blanket reducing the volatility of potentially volatile components. The Envitco dry feed demonstration was the only Phase 1 melter test in which most of the iodine (~90%) in the LLW simulant was incorporated into the glass.

Considering the limited cold-cap coverage, melt rates per unit area achieved with slurry feed appeared to be approximately equal to those achieved with dry feed. If more power had been available to maintain a higher melt temperature at higher feed rates, and multiple slurry feed nozzles used to obtain more complete cold-cap coverage, it appears likely that melt rates with slurry feed may have exceeded those obtained with the dry feed. This was an unexpected result. However, similar high melt rates with slurry feed were also demonstrated in the Phase 1 testing conducted by Vectra and Duratek. Based on these results, and the less complex equipment requirements, slurry feeding should be the first choice for future work.

The melter NO_x emission measured during the dry feed demonstration (offgas characterization was not part of the slurry feed test) was the second highest measured in any Phase 1 test. In the USBM feed preparation studies, sugar denitration reactions occur at lower temperatures than carbon denitration. Using an alternate reductant such as sugar or sugar with carbon instead of straight carbon may allow more efficient denitration to occur at lower temperatures and should be considered for future testing.

4.1.3.3 Refractory and Electrode Wear. The EV-16 test melter was rebuilt with new refractories and electrodes at the beginning of Phase 1 testing. Following testing, the melter was disassembled and the refractories and electrodes were examined. Different refractories were used as single 76-mm thick blocks for each of the four glass contact sidewalls of the melter. The four refractories tested were as follows:

- Corhart Zirchrom-30,* a sintered $Cr_2O_3/Al_2O_3/ZrO_2/SiO_2$ refractory produced by Corhart, a subsidiary of SEPR of France

*Zirchrom is a trademark of Savois Refractaires.

- Carborundum Monofrax S-4,[1] a fused cast $Al_2O_3/ZrO_2/SiO_2$ (AZS) refractory produced by Carborundum, a subsidiary of Sohio Corporation
- Serv-30,[2] a sintered Cr_2O_3/Al_2O_3 refractory produced by North American Refractory Company (NARCO)
- Vision,[3] a sintered AZS refractory also produced by NARCO.

After removal at the end of testing, the refractory blocks were sectioned and the thickness was measured at several locations to evaluate the amount of dissolution of each refractory type. The most dissolution-resistant material was the Zirchrom-30, which only lost ~1 mm of thickness along a vertical section and only ~2 mm of thickness near the electrode. The next best dissolution resistance was observed with the Monofrax S-4, which lost ~1.5 mm of thickness along a vertical section and ~3 mm near the electrode. The Serv-30 lost ~2 mm in thickness along the vertical section and ~4 mm near the electrode. The Vision refractory exhibited the least dissolution resistance, losing ~5.5 mm of thickness along the vertical section and ~10 mm of thickness near the electrode. Additional refractory examinations included degree of cracking, permeability to vapor-transported species (sulfate penetration), and detailed microscopic examination. All four refractory types exhibited several cracks.

The electrodes had larger diameter end caps that were beveled on the end that faced the center of the melter. Post-test measurements indicated ~2% to 3% of the mass of these endcaps were eroded during testing. Some minor pitting also occurred on the endcaps. Additional detailed results from the refractories and electrode examinations are provided in the Envitco Phase 1 test report (WHC-SD-WM-VI-023 [Wilson 1996]).

4.1.3.4 Melt Foaming Event. As previously described, a melt foaming or reboil event occurred at the end on the dry feed portion of the melter test after changing to the UN-4 feed lot. The UN-6 feed containing 1% Fe_2O_3 and 100% stoichiometric carbon addition was run before changing to the UN-4 feed which was batched with 110% of stoichiometric carbon addition. The glass redox ratio (Fe^{+2}/Fe) was 0.56 for the last glass sample analyzed before changing feeds. Also, had all the sulfate present in the LLW simulant been dissolved, the equivalent SO_3 content of the melt would have been 0.21%. A hypothesis for the chemical mechanism causing the reboil is that the 10% excess carbon caused further reduction of Fe and/or S in the glass melt liberating O_2, CO_2, CO, and/or SO_2 gases. The higher oxidation states of oxide components in the glass also become less stable relative to reduction reactions when the melt temperature is increased. The foaming subsided when melt temperature was reduced from ~1400 °C to ~1050 °C hot hold for slow outgassing, and the foaming increased each time the melt temperature was

[1]Monofrax is a trademark of the Carborundum Company.

[2]Serv is a trademark of NL Industries Inc.

[3]Vision is a trademark of Didier Taylor Refractories Corporation.

increased during the following several days. The melt foaming event shows the need for adequate characterization of the LLW and careful control of the melter feed batching and chemistry.

4.2 VECTRA

Vectra is a diversified provider of services to commercial nuclear utilities and the federal government. Services include design and operation of nuclear waste management processes, equipment, transportation casks, and processing systems. The Vectra Phase 1 testing was conducted under WHC contract MMI-SVV-384211. The Vectra testing was contracted through Vectra Government Services Incorporated at San Ramon, California.

4.2.1 Melter Technology Description

The Vectra melter is Joule heated with nearly vertical electrodes that enter through the top of the melter vessel. The melter is water jacketed and has a relatively thin refractory lining. A layer of frozen (or highly viscous) glass is expected to form on the walls to protect the refractory and provide a relatively long melter life. The melter is designed for nuclear service and includes features to minimize the need for complex and expensive remote maintenance capabilities (manipulators, full remote cranes, etc.). The melter is compatible with wet and dry feed.

4.2.1.1 Full-Scale Concept. For Hanford Site low-level tank waste processing, the full-scale melter will have a Joule-heated, vertical electrode design similar to the Phase 1 test melter. Two 100 ton/day melters could be provided; however, four 50 ton/day melters were suggested by Vectra to reduce melter size. It is desirable to avoid excessively large melters to facilitate handling and fabrication of the double-walled pressure vessel design Vectra has proposed, and if possible to allow for removal and disposal of failed melters as a unit (i.e., without cut up of the vessel). Estimated inside diameters for 50 ton/day melters are 4.1 and 5 m for dry feeding and slurry feeding, respectively. Overall melter vessel height is estimated at 3 m for both feed options. Table 4-2 provides a summary of key melter parameters and forecast performance for several melter capacity options.

For the 50 ton/day scale, six 10-cm diameter electrodes are proposed that have adjustable extension and tilt angle. New electrode extensions can be added and fed inward as the electrodes wear. The proposed electrode material is molybdenum; however, other materials such as chromium, carbon, or Inconel can be substituted if needed for specific processing needs. The melter concept includes a thin refractory lining (~10 cm) to reduce heat loss to the cooling water. An induction-heated freeze valve on the bottom of the melter is proposed for glass pouring (a resistance electric-heated version was tested during Phase 1). The induction valve is a cold wall design expected to have a relatively long life and reduced maintenance requirements compared to the resistance-heated design.

Based on Phase 1 test results, Vectra has concluded the slurry feed concept is preferred for the full-scale plant. In this process, plant feed is pre-concentrated if needed and mixed with reductant and dry glass formers to

form a pumpable slurry. Feed slurry is injected through an estimated three feed ports per melter. To reduce thermal load on the melter, the water content of the liquid feed is reduced as much as feasible while retaining a reliably pumpable slurry.

A detailed full-scale melter design concept has not been prepared. Full-scale design is expected to include Vectra nuclear operating and maintenance technology similar to that developed for its commercial melter system. Typical features include integral shielding of equipment and modularization to minimize the need for complex remote maintenance systems (e.g., use of manipulators, robotics, and full remote cranes is minimized or eliminated in typical Vectra designs). An example is integral shielding of the top and sides of the melter to provide relatively low local dose rates (<5 mR/h). This shielding allows operator access for most routine melter top end maintenance functions (electrode feeding and manipulating mechanisms, instrumentation, cooling water supplies and controls, purge gas, etc.). The melter consists of a double-walled pressure vessel with cooling water between the walls. Most services are provided from the top, and access to the sides is not required. This allows relatively small clearance between the melter and cell walls. Nuclear operating and maintenance designs will require scaleup and some further development before implementation.

4.2.1.2 Technology Status. The Vectra melter is an adaptation of proven Joule-heated melter technology. Vectra is planning to develop a commercial LLW vitrification system using the proposed melter technology. Commercial system operation is expected to provide additional verification of the process technology and the nuclear operation and maintenance features. The Phase 1 test melter was incorporated into a transportable LLW vitrification system following Phase 1 testing. However, further development and completion of this system was placed on hold in December 1995 and future use of this system is uncertain at the time of the current writing.

Larger commercial melters are successfully operating using similar melter/electrode designs. The cylindrical pressure vessel design concept and some of the nuclear operating/maintenance concepts appear unproven at the larger scale. The induction-heated cold wall drain valve is also unproven in this application. If this drain valve is unsuccessful, alternate designs can be used; however, they may have lower life expectancy and increased maintenance requirements compared to the induction-heated cold-wall design.

4.2.1.3 Technical Issues. Several technical issues discussed below need to be addressed in further development of the Vectra technology for the LLW vitrification facility.

Bottom Drain--The bottom drain is an important aspect of the Vectra melter design concept. It allows use of a double-walled pressure vessel design that is relatively simple, compact, and space efficient. Another advantage of a bottom drain is that refractory and settled non-vitrified sludge is purged from the melter during normal glass pouring. However, use of a bottom drain for normal glass pouring is considered to carry a higher risk from a drain control and safety perspective compared to overflow designs. While Vectra presumably could design a melter with overflow glass pour, it

Table 4-2. Summary of Key Melter Parameters and Forecast Performance.

Item	Phase 1 dry feed	Phase 1 slurry feed	10 TPD dry feed	50 TPD dry feed	50 TPD slurry feed	100 TPD dry feed
Outside diameter (m)	1.31	1.31	2.29	4.42	5.18	6.94
Net ID (m) (refractory ID)	0.98	0.98	1.98	4.08	4.82	5.58
Melter overall height (m)	1.68	1.68	2.58	3.05	3.05	3.35
Melter cross-sectional area (m^2)	0.75	0.75	3.08	13.0	18.1	24.6
Throughput basis:						
Dry feed ($kg/m^2/h$) (glass equivalent)	146	107	146	146	107	146
Melter size factor[a]	1.0	1.0	1.1	1.15	1.15	1.2
Design basis glass production ($kg/m^2/h$)	146	107	161	171	122	176
Active glass surface area (m^2)[b]	0.57	0.57	2.60	12.1	17.2	23.7
Total design throughput (metric TPD)	2	2	10	50	50	100
Scaleup factor	Basis	Basis	5.0	5.0	5.0	10.0
Power rating, kW[c]	140	160	350	1050	1200	1600
No. electrodes	3	3	3	6	6	12
Electrode diameter (cm)	6.35	6.35	10.2	10.2	10.2	10.2
Electrode material	Moly	Moly	Moly	Moly	Moly	Moly
Glass depth (cm)	51-76	51-76	106-122	122-152	122-152	122-152
Glass volume (m^3)	0.57	0.57	4.25	17.0	24.9	34.0
Electrode current density (amp/cm^2)	1.41	1.41	0.82	1.24	1.41	0.93
Waste feed ports						
Number	One	One	One	Three	Three	Four
Size, ID (cm)	40.6[d]	40.6[d]	15.2[e]	15.2	15.2	15.2
Offgas ports						
Number	One	One	One	One	One	One
Size, ID (cm)	40.6[d]	40.6[d]	45.7[e]	50.8	50.8	61
Weight[f]						
Empty (kg)	8,300	8,300	25,000	70,300	88,400	129,250
Operating (kg)	9,750	9,750	36,300	113,400	152,000	217,700
Glass drain	One	One	One	One	One	One
Glass drain type	Joule-heated ring	Joule-heated ring	Induction-heated nozzle	Induction-heated nozzle	Induction-heated nozzle	Induction-heated nozzle
Materials of construction	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary

[a] Adjustment factor for improved throughput due to increased glass mixing of larger melter, estimated 10 ton/day integrated melter system to verify rate.

[b] Active glass area equals melter refractory inside diameter cross-section area less inactive cool area at glass/gas interface (cold edge effect) around inside perimeter of melter.

[c] Power required to operate melter at design throughput. Actual power supply multitap transformer to be 50% larger capacity.

[d] Phase 1 melter has one common 40.6-cm waste feed/offgas port.

[e] Offgas and feed ports form concentric areas in a common 45.7-cm access port.

[f] Weight includes all components registered by load cells, such as lid, refractories, shell, feed connection, built-in shielding, electrodes, glass, nozzle attachments, etc.

ID = Inner diameter

would appear to result in a major revision of the basic melter vessel and melter cell design concept. A reliable bottom drain is therefore considered important to the success of the Vectra melter concept.

During Phase 1 testing, Vectra used a drain ring located in the center of the melter bottom for glass pouring. The drain ring is heated by passing an electric current through it to the glass pool. A water-cooled stopper plug inserted in the ring pour hole quickly stopped glass flow. Flow was restarted by removing the stopper plug and turning up power to the pour ring to melt the plug of frozen glass. The pour valve was reliable during the Phase 1 testing; however, some manual operator actions were required to keep it operational. It appears that for this drain valve design, some additional remote maintenance features will be needed, for example, to clean off frozen glass drips or deposits around the pour hole that can make it difficult for the stopper plug to seal the drain orifice. The drain orifice was not appreciably worn by the Phase 1 testing; however, in continuous operation it may be anticipated that the orifice will gradually get larger. Additional external orifice plates can be added or the drain ring can be replaced; however, special remote tooling and equipment concepts will need to be developed to allow this work to be performed without excessively exposing workers to radiation. A backup shut-off method also may be required to cut off glass flow if the primary stopper valve fails.

There is little or no experience in long-term continuous operation with a bottom drain in similar applications. The industry consultants participating in the melter testing program indicated there is a history of problems with bottom drains in the glass industry. This is therefore considered an area of relatively high risk that could result in significant operational problems and is likely to require attention in development, design, and operation.

Maintenance Concepts--One advantage of the Vectra design concept is that the melter and other nuclear process equipment are designed to reduce the need for facilities with heavy remote mechanical maintenance capabilities (manipulators, robotics, full remote cranes, etc.). This design also reduces the need for high-tolerance equipment and remote 'jumpers.' If successful, this approach will significantly reduce construction time and cost for the process facility as compared with fully remote facilities. This approach may require use of innovative and untested operating and maintenance concepts. This new technology will need to be developed, tested, and debugged as part of the overall process development program. The nuclear operating and maintenance system technology may be more important to the overall program cost and schedule than the basic process technology.

Melter changeout and packaging for disposal is an important aspect of the overall maintenance concept. The Vectra concept is to design modular equipment (including the melter) that can be disposed of as a unit, without need for a cutup cell. Additional work is needed to define the overall melter removal, replacement, and disposal concept. This work should include better definitions of packaging, and transportation requirements for failed melters and other large failed equipment.

Effect of Feed Compositions--Better information is needed regarding the effect of other melter feeds with increased salts concentration and impacts from recycle of offgas scrubbing wastes. The feed limits to avoid salt

removal features need to be determined. Some testing with real feeds would be desirable to determine any unexpected behavior of real feeds versus simulants.

Achievable Melt Rate and Scaleup--There is significant uncertainty in scaleup factors to design a 50 ton/day glass capacity melter that are proposed by Vectra for the LLW vitrification facility. Good cold-cap spreading was observed with slurry feeding during Phase 1 testing. However, Phase 1 melt rates were <1 tonne/day compared to 1 to 2 tonne/day melt rates expected by Vectra. Lowest melt rates were obtained with calcined feed. Added design features such as inert gas bubbling and plenum heaters could be incorporated, along with reactive glass-former additives and feed optimization, to enhance melting rates.

Electrode Performance--The use of vertical top-entering electrodes with a bottom drain melter design raises special issues in regard to electrode performance. Significant wear of the molybdenum rod electrodes occurred during Phase 1 testing. Some of this wear likely occurred when the melter was drained at the end of testing when the hot electrodes were exposed to air. However, much of the electrode wear also may have occurred during glass pouring operations during testing when the glass level may have been dropped sufficiently to expose the Mo below the protective sheathes. This resulted in rapid loss of electrode material eventually causing the end of two electrodes to break off during melter operation. Controls will be needed to ensure that melt level is not drawn down to the point during operation that the electrodes are exposed. Inert gas purging of the melter plenum along with effective feed reductant additives to maintain inert or reducing gas above the melt also may be required, particularly if the glass level is not maintained above the bottom of the electrode sheathes. Other electrode materials such as graphite, Cr metal, or other refractory metal also should be evaluated as a potential means for improving high-temperature electrode performance.

Refractory Life--Vectra uses a relatively thin (~10 cm thick) refractory layer to line the water-cooled inner shell of the melter, and relies on the maintenance of a frozen or viscous glass skull layer to contain the glass melt and protect the refractories and inner melter shell from wear. The life of this relatively thin refractory layer and performance of the skull layer melting high-alkali glass formulations are unknown.

4.2.1.4 Technology Strengths. The following strengths are identified for the Vectra Ve-Skull melter technology.

- Likely as a result of Vectra's nuclear service industry experience, the Vectra melter technology appears to be particularly innovative in consideration of features and requirements for radioactive remote operation and maintenance.
- Use of Joule heating will likely result in relatively low volatility and entrainment losses of feed components when operated in a cold-top mode.
- If a safe, controllable, and reliable bottom drain can be demonstrated, settled sludge will be purged from the melter during normal glass pouring operations. Potential refractory erosion products and LLW feed components, such as Cr, and associated

liquidus temperature issues that may limit waste loading will be of much less concern than with overflow drain designs. However, glass level control so as not to expose top-entry molybdenum electrodes may still be an issue.

4.2.2 Phase 1 Testing

Melter testing was performed by Vectra at its facility in Richland, Washington. Vectra is constructing a modular waste processing system to vitrify commercial low-level nuclear waste, originating primarily from nuclear power plants. Vectra performed Phase 1 testing using the same melter to be installed in the commercial waste vitrification system. Detailed discussions of the Phase 1 testing and results are provided in WHC-SD-WM-VI-031 (Stegen 1996). The test melter and feed system configurations are shown in Figure 4-4. The melter operated for 31 days during Phase 1 testing and produced ~10 tonne of glass.

Three approaches to melter feed preparation (two dry feeds and slurry feed) were tested as described below.

Calcination--Fluid bed calciner testing was performed by Procedyne at its facility in New Brunswick, New Jersey. Approximately 500 kg of calcined dry melter feed were produced in a 2-day semicontinuous calcination demonstration.

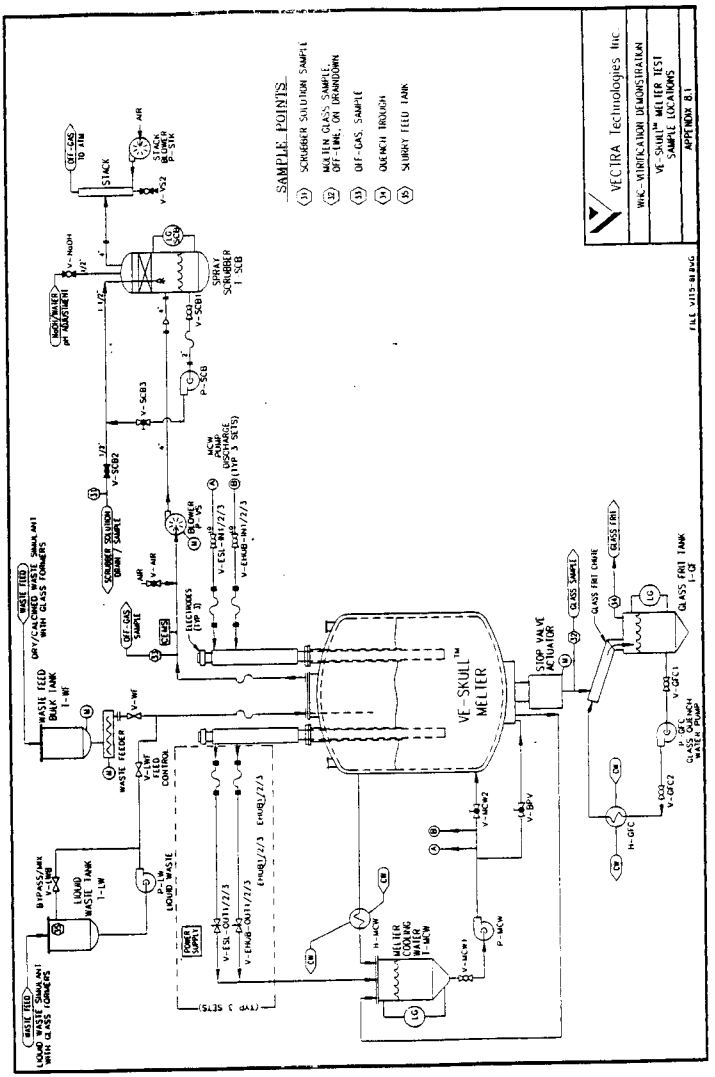
RVR Dryer--Blended dry glass former and sugar reductant mix, and liquid LLW simulant, were fed to an RVR dryer. The RVR dryer contained two counter-rotating paddle augers in a heated shell. The augers and shell were heated to ~200 °C by hot oil flowing through the auger cores and shell jacket. The goal with the RVR dryer was to produce a granular de-nitrated dried feed.

Slurry Feed--Batched slurry feed was prepared and fed in a conventional manner as shown in Figure 4-4.

4.2.2.1 Test Melter. The melter is a double-shelled cylindrical pressure vessel. The refractory-lined inner vessel has a 1 m inside diameter and is water jacketed by the outer vessel. Three vertical top-entering molybdenum rod electrodes were used. Tilt angle and extension of electrodes may be remotely adjustable when the melter is installed in the commercial vitrification system; however, tilt angle was fixed for Phase 1 testing.

The test melter has a single feed port which is in common with the offgas port. For slurry feeding, the feed tube extends down through the offgas port discharging near the center of the melt pool a short distance above the melt. For dry feeding, an auger is used to transfer granular or powdered feed from a hopper into the feed/offgas port from which it falls to the top of the melt pool. Feed rate with the auger exceeds melter capacity so that intermittent on/off feeding is required for dry feeds. The melter has a single drain port located in the center of the bottom. The bottom drain ring is a thick metal disc with an approximate 2-cm hole bored through the center and is electrically isolated from the melter shell. The drain ring is heated by passing a current through it to the glass pool. Once initiated, the glass flow is stopped by inserting a water-cooled plug into the drain hole. The

Figure 4-4. Configuration of Vectra Technologies, Inc. Phase 1 Test Melter and Feed System.



plug is tapered, facilitating removal to restart glass flow. The glass pour stream was quenched in a flowing water stream, except at the end of testing when 'monolith' pouring into metal drums was demonstrated.

Expected capacity of the test unit is up to ~2 tons glass/day depending on feed stock. The commercial melter equipment and process system are described in more detail in *Vitrification Melters for Low-Level Radioactive and Mixed Wastes* (Mason 1995) and *Modular Enviroglass Vitrification Technology for Low-Level Radioactive and Mixed Wastes* (Mason 1994). Dimensions and other specifications are presented in Table 4-2 for the Phase 1 melter and for scaled-up versions.

4.2.2.2 Glass Formulation and Feed Batching. The target glass formulation and glass-former additives selected by Vectra for Phase 1 testing are presented in Table 4-3. Powdered sugar (sucrose) was used as a feed reductant additive for most feed preparation; however, ammonia, methane, and hydrogen also were tested as reductant additives during calcination scoping tests. Various amounts of sucrose addition ranging from 75% to 600% of stoichiometry required for NO_3^- reductions were tested in scoping tests with 100% stoichiometric sucrose addition selected for most production test runs.

4.2.2.3 Feed Preparation. The fluidized bed calciner process tested by Procedyne used a conventional 41-cm diameter commercial fluidized bed unit operating at ~500 °C. Dry glass-former powders and liquid LLW simulant with added reductant (sucrose) were added separately to the bed. When operating at steady state, glass formers and liquid waste simulant were continuously metered in at rates required to achieve desired glass composition. Nitrogen used for fluidizing gas was preheated before entering the vessel. Additional heat for drying and calcining reactions was supplied by exothermic reactions between the reductant (sugar) and NO_3^-/NO_2^- in the LLW simulant, and by heat

Table 4-3. Vectra Target Glass Formulation and Batch Materials.

Component	Wt%	Source
SiO_2	52.8	Silica sand
B_2O_3	8.0	Boric acid
Na_2O	20.0	DSSF simulant
Al_2O_3	10.0	DSSF simulant, alumina trihydrate
CaO	2.9	Dolomite
MgO	2.1	Dolomite, magnesium carbonate
Fe_2O_3	1.0	Iron oxide
Other	3.2	DSSF simulant
Total	100.0	--

DSSF = Double-shell slurry feed

transfer through the vessel walls. Offgas from the bed passed through filters located in the top of the vessel. Periodically, each filter element was blown back to dislodge accumulated solids which fell directly into the fluid bed below. At the bottom of the fluid bed is a cone-shaped gas distributor with a drain pipe in the center. Reacted bed material accumulates to fill the drain pipe. During normal operation, calcined feed is removed using a screw auger at the bottom of the drain pipe in a continuous or semicontinuous manner.

An RVR rotary paddle-type dryer/calciner process was tested during Phase 1. In this process, the LLW simulant with added reducing agents was added to a rotary calciner. Dry powdered glass formers were added separately. With this process, glass formers and liquid simulant are blended while they are heated, water is driven off, and reactions with the reducing agent destroy most of the NO_3^- and NO_2^-. The test system was heated with recirculating hot oil to a maximum temperature capability of ~300 °C. The RVR-dried feed was to be used for most of the Phase 1 testing. However, because of caking problems in the RVR dryer, only a small quantity of the RVR-dried feed was actually produced.

Because of the limited amount of dried feed available (calcined and RVR dried), a simulated dry feed referred to as V-Sim feed was prepared. The V-Sim feed was made by blending dry powdered chemicals to achieve the target glass composition, including all minor components present in the DSSF simulant. Sodium was added primarily as carbonate with a small amount of NO_3^- and powdered carbon also added to simulate residual nitrogen and organic carbon in the calcine.

A slurry feed process was used for most of the Phase 1 testing time during which offgas measurements and samples for mass balance evaluations were taken. Slurry feed was prepared by blending liquid simulant with pre-mixed glass formers and sugar (100% stoichiometric addition) in a weighed mixing tank. Smaller batches of the resulting mix slurry were transferred using a pumped recirculating loop to an agitated day tank located near the top of the melter. Feed was drawn through a dip tube from the day tank through a peristaltic metering pump and then to the melter feed tube. The level of the day tank was monitored and each batch quantity transferred to the day tank was determined by weight.

4.2.2.4 Test Monitoring and Sampling. Melter input and outputs were measured as follows.

- Feed--Instantaneous slurry feed rate was controlled by the setting of the delivery rate of a peristaltic pump. Dry feed batches added to the feed hopper were weighted and the weight measurements of feed batch transfers were used to estimate average dry feed rates. Measurements of the glass level in the melter were made with a rod inserted from above the melt surface to estimate glass inventory accumulation rates between glass pouring periods.

- Glass--The melter was supported on load cells that permitted continuous monitoring of changes in weight allowing estimation of changes in glass inventory. Glass poured during each batch pour could then be estimated by correcting measured inventory change during the pour for any feed added during the pour.

- Offgas--Offgas flow and composition were only measured during material balance test segments. These measurements were obtained by an independent contractor using standard EPA methods.

Melter power and voltage for each phase were monitored during the test, and a closed-circuit television camera was used to continuously view the center portion of the melt pool surface. Direct measurement of the glass pool temperature was unavailable during the test.

Glass samples were taken from each batch pour after the startup period. Samples of feed slurry and dry feeds also were taken.

4.2.2.5 Test Chronology. Melter testing proceeded through three major testing segments and startup shakedown testing. Duration and glass production during each test segment are summarized in Table 4-4. Test segments are summarized below.

Startup (MT-1)--The melter was new and had not been heated up before this test period. The melter was filled with startup glass cullet and preheated with a gas burner until glass conductivity was sufficient to allow heating with the electrodes. Additional glass cullet was fed while shakedown tests were performed and startup problems were resolved. Once operations experience was obtained and glass draining became relatively routine, the melter was ready for testing with the target glass formulation and feeds were prepared using the simulated DSSF LLW.

Table 4-4. Test Segment Run Data Summary.

Test phase	Test duration (hours)	Total feed (kg)	Total glass product (kg)	Graphical average feed throughput (kg/h)	Graphical peak feed throughput (kg/h)	Peak feed throughput ($kg/h\text{-}m^2$)[a]	Glass in feed (wt%)	Calculated peak glass throughput ($kg/h\text{-}m^2$)	Average power (kW)
Startup	217.2	1,658.0	0.0	--	--	--	--	--	82.3
MT-1: Vectra-Glass	253.2	5,400.9	3,886.2	30.2	88.5	156.2	75.0	117.1	91.0
MT-1: Idle	73.0	134.7	136.1	2.2	2.2	3.9	75.0	2.9	82.7
MT-1: Slurry	102.2	3,563.1	1,437.2	36.2	77.3	136.4	57.0	77.8	114.0
MT-2: Slurry	14.0	864.6	406.3	59.9	59.9	105.6	57.0	60.2	138.6
MT-3: V-Sim	3.0	99.8	68.5	43.2	43.2	76.2	75.0	57.1	115.6
MT-4: Calcined	4.0	161.7	136.1	25.7	25.7	45.3	95.0	43.0	84.4
High throughput: V-Sim	58.5	2,808.6	2,100.7	47.4	71.0	125.2	75.0	93.9	119.4
High throughput: Slurry	5.8	374.4	310.2	67.5	67.5	119.1	57.0	67.9	121.3
High Na	8.2	408.2	239.5	40.0	40.0	70.6	75.0	52.9	106.4
Final drain down	--	--	917.0	--	--	--	--	--	--
Total Phase 1[b]	768.7	16,434.1	10,173.7	--	--	--	--	--	96.9

[a]Active area = gross glass pool area 0.75 m^2 minus assumed 10-cm radial cold zone along wall = 0.57 m^2.
[b]Totals include feed and drain during transition periods between tests.

Vectra = Vectra Technologies, Inc.

Slurry Feed Startup (MT-1)--The cullet base material used for startup did not contain all minor components present in the DSSF simulant. Therefore, the melter was operated with slurry feed for several days to allow buildup of minor components to near steady-state levels before performing material balance test segments. Minor problems, including plugging of the feed line, were encountered early in the test with the slurry feed system. Some trial and error also was needed to determine the maximum feed rate the melter could tolerate. This resulted in intermittent feeding early in the slurry feed test. Once problems were worked out of the feed system and the operators understood the melter operating characteristics with slurry feed, the slurry feed test went relatively smoothly.

Slurry Feed Testing (MT-2)--Initial simulated LLW testing was performed using a slurry feed in test segment MT-2. This test segment followed ~4 days running with slurry feed at the end of the MT-1 startup segment in which the melter was brought to a near compositional steady-state condition. Analyses of glass samples taken during test segment MT-2 indicated that concentrations of DSSF minor components excluded from the startup cullet-based feed were still increasing during the material balance test segments. This indicated that a steady-state condition was not completely achieved at the end of slurry feed run segment MT-1. Average glass melting rate during slurry feed run segment MT-2 was estimated to be 0.82 tonne/day, or 60 $kg/m^2/h$.

Two material balance test segments that included offgas characterization along with feed and glass sampling were performed near the end of the slurry feeding test. Offgas sampling was performed by an independent contractor using standard EPA methods.

Simulated Calcine Test (MT-3)--After the slurry feed test, a test was performed using a powdered feed material intended to simulate a product from fluid bed calcining (this feed is referred to as V-Sim). Operation with V-Sim feed was intended to allow the melter to attain relatively steady-state operation with a dry feed material similar to the calcine before feeding the relatively small amount of actual fluid bed calciner product that was available. The V-Sim feed was made by blending dry powdered chemicals to achieve the target glass composition. A small amount of NO_3^- and powdered carbon also was added to simulate residual nitrogen and organic carbon in the calcine. Operation with V-Sim feed continued for 3 hours including a material balance test segment near the end of this period. Average glass melting rate for run segment MT-3 was 57 $kg/m^2/h$.

Calcine Feed Test (MT-4)--Calcine feed was prepared by blending products from the fluidized bed calcining test with boric acid to achieve the target glass composition. Immediately after completing the V-Sim simulated calcine test, calcine feed was started and continued for 4 hours. A material balance test segment was performed near the end of this period. Average glass melting rate for the calcined feed is estimated to be only ~43 $kg/m^2/h$.

Throughput Tests--After the primary test segments were complete, the melter was operated for 3 days to further explore operation characteristics and to attempt to achieve higher throughput rates. Glass melting rates estimated during this segment running V-Sim and slurry feeds were 62.4 and 67.5 $kg/m^2/h$, respectively.

Draining and Inspection--After the throughput tests, the melter was drained, cooled down, and inspected. The electrodes were removed and photographed. Accumulated materials in offgas lines were sampled and characterized.

4.2.3 Results and Observations

4.2.3.1 Melter Test Results. Melter tests were performed with three different simulated feeds (slurry, V-Sim calcine, and the Procedyne-prepared calcined feed). Quantities of feed melted and throughput details for these run segments are summarized in Table 4-4.

In the first tests performed with liquid slurry feed, the DSSF simulant with ~10 mol/L Na was mixed with sugar (100% stoichiometric reductant to react with NO_3^- and NO_2^-) and powdered glass formers (silica, alumina, dolomite, and boric acid). The resulting slurry was relatively fluid and could be easily pumped. Some suspended particles settled fairly rapidly, and it was therefore necessary to keep the slurry well agitated and avoid leaving slurry in piping with low or no flow. Slurry feed processed easily in the melter. The slurry spread over most of the glass pool surface (~1 m diameter) using a single feed tube pouring vertically over the center of the melt area.

The second feed processed was the V-Sim simulated calcine. Simulated calcine was fed at ambient temperature, and it was not possible to test effects of feeding hot calcine during Phase 1 testing. The simulated calcine processed reasonably well in the melter, although melt rates were lower than expected. In Vectra's original concept for an integrated production system, the hot calcine (expected to be at nominally 500 °C) would likely be directly fed from the calciner to the melter, potentially increasing melt rates.

After achieving approximate steady-state operating conditions with the simulated calcine, the feed was switched to the actual calcine from the fluid bed calciner test. Before feeding the melter, the calcine was dry blended with boric acid to achieve the target glass formulation boria level. This test showed the calcine was difficult to melt compared to slurry and V-Sim simulated calcine. Crucible melting tests run with this calcine also indicated it was slow melting.

Overall, the melter functioned well during all tests. A resistance electric-heated drain ring on the bottom of the melter with a water-cooled shut-off plug was used for glass pouring. Initially, it was difficult to sufficiently heat the drain ring to get adequate electrical conductivity through relatively cold glass in the bottom of the melter. However, once the initial pour was established and electrical power parameters were stabilized, pouring became routine and could be started and stopped with little difficulty. For the full-scale plant melter, electrodes will be adjustable so they can be extended nearer to the drain port, thus allowing faster initial heatup and easier initial draining.

Severe 'corrosion' of electrodes was experienced during the Phase 1 testing. Electrode material was lost near the upper melt level to the point that the ends of two of the electrodes broke off. Water-cooled protective sleeves around the electrodes were originally designed to prevent exposure of

electrodes to the atmosphere in the top of the melter. However, water jackets on the original electrode sleeves were cracked when received and the repaired electrode sleeves were not water cooled and became eroded at their lower ends providing less protection to the electrodes as testing progressed. Melt level was allowed to drop below the eroded protective sleeves several times during the test, thus allowing the molybdenum electrode to be exposed to the plenum atmosphere. Molybdenum oxidizes rapidly in air at melt temperatures. The ends of the electrodes that were always submerged in the glass pool were not as severely corroded. This experience points to the importance of engineered controls and operating practices that reliably maintain glass melt level high enough to prevent exposure of electrodes to the melter plenum atmosphere.

A small amount of refractory mortar was in setting the refractories that lined the melter inner vessel. Significant loss of the mortar between the refractories was seen during the test. Vectra has suggested that reducing the spacing between refractory pieces would reduce the effect of mortar loss. Significant attack on the refractory was not otherwise noted in the visual inspection.

4.2.3.2 Fluidized Bed Calciner Test Results. Initial bench-scale fluidized bed tests were performed in a 15-cm diameter batch reactor. A batch of glass-former powders was placed in the reactor and heated to the desired temperature with a constant flow of fluidizing gas. When the desired temperature was reached, liquid LLW simulant was fed to the bed at a metered rate. When the desired feed simulant to glass-former ratio was reached, the bed was cooled and removed for examination. Reductant additives were added, which were intended to react with NO_3^- and NO_2^- in the feed. A number of bench-scale tests were performed using different operating conditions and different reductant additives (sucrose, ammonia, methane, and hydrogen) in an attempt to identify conditions and additives that result in an operable bed with acceptable performance. When using boric acid or boric anhydride as the boria source, the target level of boria could not be added without caking up the bed. Higher melting boria sources such as calcium borate may solve this problem; however, it was not possible to test these additives during Phase 1 testing. Therefore, it was necessary to blend boric acid into the calcine before feeding it to the melter to achieve the desired glass composition.

Bench-scale tests indicated the bed was operable at 500 °C with sugar added to the simulant as a reductant (75% to 125% of stoichiometric). All other conditions and reductant additives tested resulted in unacceptable operations, generally because of loss of fluidization caused by agglomeration of bed materials. The calcination process successfully decomposed >95% of the NO_3^- and NO_2^- in the feed. During the continuous pilot-scale test with 100% stoichiometric sugar, NO plus NO_2 in the offgas amounted to 3.3% of feed NO_3^- plus NO_2^-. Nitrous oxide (N_2O) amounted to 0.22% of feed NO_3^- plus NO_2^-. The bench-scale batch tests showed conversion to NO plus NO_2 varied with the amount of sugar added. Typical NO plus NO_2 concentration for the bench-scale test is shown in Table 4-5.

A small fraction of nitrogen in the feed also was converted to ammonia. The balance of feed nitrogen is assumed to have been converted to N_2 gas, although it was not possible to actually measure nitrogen produced during the tests.

Table 4-5. NO_x Produced During Fluid Bed Calcination[a] as a Function of Sugar Reductant Additions.

Reductant addition percent of stoichiometric[b]	NO + NO_2 in offgas ppm by volume
75%	6,000
100%	2,000
125%	<500

[a]Bed operating at 500 °C.

[b]Based on conversion of feed NO_2^-/NO_3^- to N_2 + CO_2 + H_2O. EDTA in the feed is included in the calculation and contributes ~25% of the stoichiometric reductant; sugar provides the balance.

4.2.3.3 RVR Dryer Test Results. Initial RVR dryer tests were based on a process wherein the liquid LLW simulant mixed with the reductant additive, and blended dry glass formers were added separately to the RVR dryer where they were mixed, dried, and reacted/calcined in a single stage. Tests with this single-stage process were unsuccessful due to the presence of low melting salts in the feed that caused hard caked material to form in the RVR dryer. Process changes may eliminate these problems; however, further work was abandoned because of more promising results from the fluidized bed calcining and slurry feeding approaches.

4.3 PEI

Penberthy Electromelt International, Inc. of Seattle, Washington (formerly Penberthy Electromelt Company) and its founder, Mr. Larry Penberthy, were principal early developers of electric Joule-heated glass melting technology in the United States. Applications included electric boosting of existing combustion-fired melters and all-electric melters using sidewall and bottom-entering molybdenum metal rod electrodes. During the 1970's and early 1980's, PEI advocated high-temperature calcia-alumina-silica glass and cold-top electric melting for nuclear waste immobilization, and built demonstration melters for the DOE West Valley and Mounds Laboratory Sites. Phase 1 testing conducted by PEI was performed under WHC contract MMI-SVV-384217.

4.3.1 Melter Technology Description

The PEI melter is a high-temperature Joule-heated melter that uses sidewall molybdenum rod electrodes and thick ceramic refractory blocks in glass contact areas. The melter is fed a damp mixture of absorbent glass-former additives, liquid LLW, and organic reductant additives. A thick full-coverage cold-top batch blanket is maintained over the glass melt to provide low volatility and feed entrainment losses. As with slurry feeding, feed drying, NO_3^-/NO_2^- reactions with feed reductant additives, and melting all occur in the melter.

The PEI mix-in-the-charger melter feed system requires minimal radioactive materials processing equipment. The liquid LLW stream is injected directly into screw charges where it mixes with pre-blended, nonradioactive, absorbent glass-former additives and creates a damp feed that is directly fed to the melter. Another unique feature of the PEI melter is the offgas filter alcove containing ceramic fiber filters where the offgas exits the melter plenum. When the first filter element adjacent to the melter interior becomes loaded with filtered material and shows increased pressure drop, it is pushed into the melter it melts with the LLW feed.

4.3.1.1 Full-Scale Concept. PEI did not provide a description of a full-scale LLW melter system design with supporting technical information and specifications as requested by the SOW (Wilson 1994). In discussions, Mr. Penberthy recommended melters sized from 25 to 50 tonne/day glass production capacity for the LLW vitrification facility. PEI expected glass melt rates of 40 to 45 kg/h (80 to 90 $kg/m^2/h$) (Kelly 1995). Assuming a melt rate of 80 $kg/m^2/h$ could be achieved with the damp feed, ~26 m^2 of melting area would be required for 50 tonne/day. However, specific melt rates with the mix-in-the-charger damp feed were not measured during PEI Phase 1 testing.

The full-scale melter would be fed by multiple screw chargers that would drop feed at multiple locations across the melt surface. Each screw charger could drop feed from multiple holes along the length of the screw charger barrel as well as from the end of the charger. The full-scale melter likely would require about six or eight screw charges to achieve good batch coverage. The glass-former additives required to achieve the target glass composition would be mixed in a nonradioactive area of the plant, or could be purchased mixed to specification by an offsite vendor.

4.3.1.2 Technical Issues. This section summarizes the technical issues that need to be addressed to implement the PEI melter concepts in the LLW vitrification facility.

Feed Composition Control--Two feed streams, the liquid LLW and dry glass-former mix, need to be independently metered to control the feed composition with the PEI feed system. With slurry feed systems, the slurry feed is usually mixed in a batch makeup tank and can be analyzed to confirm its composition before it is advanced to the melter feed tank and fed to the melter. With the mix-in-the-charger feed system, the feed composition cannot be confirmed before it is injected into the melter. Therefore, accurate characterization of the LLW stream and accurate and reliable metering of the LLW and glass-former streams are critical to process control and achieving the desired product glass composition. Metering control on the PEI feed chargers used for Phase 1 testing was crude, and because prolonged testing under steady-state operating conditions was not achieved, product glass composition control with this feed system was not demonstrated.

Batch Blanket Control--A glass industry consultant has expressed concern regarding the potential for batch blanket bridging operating with full cold-top dry batch coverage. Bridging did not appear to be a problem during the 10 hours of melter operation feeding the charger mixed feed. However, crust control and avoidance of bridging will need to be verified with the final

melter and feed system designs. The formation of 'icebergs' of unmelted feed reaching deep into the glass pool under points where feed is dropped from the screw chargers also may be a problem for smaller melters.

Reboil/Melt Foaming--As previously discussed relative to the Envitco melter, the potential for melt reboil or melt foaming upsets is an issue with all glass melters that contain a large pool of melting glass when processing feeds with potentially variable chemistry. Reboil or melt foaming upsets are usually caused by redox reactions in the glass melt that liberate gases such as O_2, CO, CO_2, and SO_2. Gas release and foaming also may result from increasing melt temperature. A clear understanding of the LLW characteristics, correct feed formulation, and good temperature control will be important considerations in preventing reboil/melt foaming upsets.

Moderate melt foaming occurred during the last night of attempted Phase 1 testing activities at PEI. This foaming was likely a result of an incompletely melted and equilibrated batch being submerged while carbonate batch was added at reduced power and temperature after the bottom drain loss-of-control event. Melt foaming occurred when power was increased to return the melter to operating temperature and melt the fresh batch.

Electrodes--It may be a particular challenge to incorporate design features to allow remote adjustment, maintenance, and replacement of the PEI sidewall electrodes. Discussions of potential electrode maintenance issues with Mr. Penberthy were vague and indicated a potential concern. One approach may be to use conservatively large electrodes designed for the life of the melter. In the test plan (Kelly 1995), PEI points to commercial container glass experience where 'little or no wear on electrodes after two or more years of melting amber bottle glass' is observed. However, the LLW feeds likely will contain corrosive salt components such as Cl, F, SO_4, and PO_4, and also may contain trace reducible metal components such as Cu, Ni, and Sb that may potentially attack molybdenum electrodes. Extended testing of the sidewall electrodes with representative LLW feeds likely will be needed to verify the long-term electrode performance and/or electrode maintenance procedures.

Melter Drains--The drain design for the PEI melter is uncertain. The failure of three lower sidewall drains, followed by a bottom drain loss-of-control event, was the immediate cause for the early termination of Phase 1 testing at PEI. A reliable overflow-type drain system for normal pouring of the LLW product glass, and a bottom drain that periodically removes settled sludges and glass at the end of the melter life, will likely need to be developed.

Remote Operation and Maintenance--To different degrees, remote operation and maintenance issues exist with all the melter technologies tested. For PEI, particular issues to be addressed include adjustment and maintenance of the sidewall electrodes, maintenance of the screw charger, operation and maintenance of drains, monitoring of sludge/metals buildup and handling of secondary waste, and monitoring and control of the batch blanket.

4.3.1.3 Technology Strengths. The following strengths are identified for the PEI melter technology:

- Maturity of technology (molybdenum electrode Joule-heated melters in many configurations have been used in the commercial glass industry for more than 40 years)
- Low volatility and entrainment losses and high waste DFs encountered when the melter operated in the full batch coverage cold-top mode
- Minimal radioactive materials handling is associated with the mix-in-the-charger feed system. With metering control upgrades needed to ensure product composition control, the simplicity of this melter feed system appears to be attractive.

4.3.2 Phase 1 Testing

A letter order to begin Phase 1 test planning was awarded to PEI on July 26, 1994. Final revisions to the PEI Phase 1 test plan were approved on January 5, 1995, and the test plan was subsequently issued for public release (Kelly 1995). Although a few days of melter operation for Phase 1 testing occurred during January 1995, technical difficulties resulted in early test termination and failure to complete Phase 1 testing objectives.

4.3.2.1 Test Facilities. Phase 1 testing was conducted at the PEI facility in Seattle, Washington. A small existing melter was re-blocked and fitted for Phase 1 testing. After re-blocking, this melter had ~0.5 m^2 of melt area and a useful glass depth of 45 cm. The predicted melt rate was estimated to be ~1 tonne/day with the damp feed.

Three types of fused-cast refractories were used for the sidewalls to evaluate refractory performance with the high soda content LLW glass formulation. The three refractory materials were as follows:

- Corhart Unicor 1, a 40% ZrO_2 AZS material
- Carborundum S-3, a 33% ZrO_2 AZS material
- Corhart ER 2161, a 27% Cr_2O_3 $Al_2O_3/ZrO_2/SiO_2$ material.

The sidewall blocks were 60 cm high by 20 cm thick. Two molybdenum rod electrodes extending through diagonally opposed ends of opposite sidewalls extended more than halfway across the melter interior. The electrodes were fired single phase across the melter, firing mostly from their sides. Three electric resistance-heated drains were installed through a lower non-electrode sidewall, and were designated from right to left as drains A, B, and C. The three drain tubes had different inside diameters (9/16, 5/8, and 11/16 in. for drains A, B, and C, respectively) to allow matching of a drain glass pull rate with the melt rate achieved under steady-state operating conditions. An existing bottom drain also was retained.

The configuration of the pilot-scale demonstration melter with feed preparation and offgas systems is shown in Figure 4-5. Detailed equipment

Figure 4-5. Penberthy Electromelt International, Inc. Test Melter, Feed System, and Offgas System Configuration. (2 sheets)

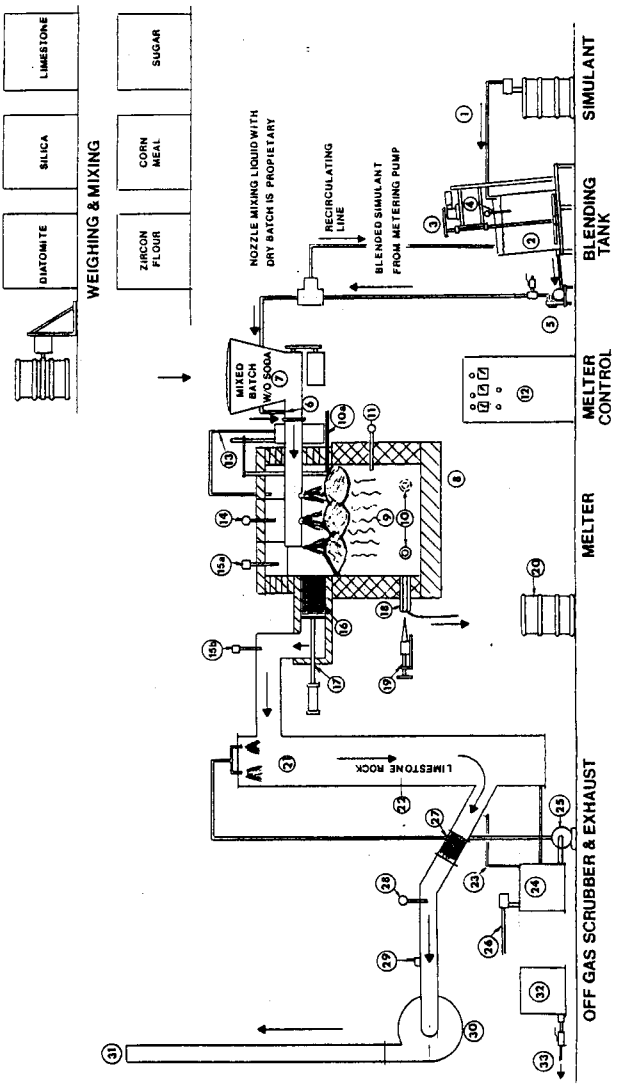


Figure 4-5. Penberthy Electromelt International, Inc. Test Melter, Feed System, and Offgas System Configuration. (2 sheets)

LEGEND

1. Low-level waste simulant from drum
2. Low-level waste simulant holding reservoir
3. Long-arm agitator
4. Thermometer/thermocouple
5. Metering pump
6. Low-level waste simulant inlet to screw charger barrel
7. Screw charger with dry materials hopper
8. Melter
9. Molten glass
10. Melting electrodes with water-cooled holders
10a. Removable carbon-arc startup electrodes
11. In-glass thermocouple
12. 200-kVA silicon-controlled rectifier melter power supply
13. Level control
14. Crown thermocouple
15a. Differential pressure tap - melter plenum chamber
15b. Differential pressure tap - between filter and scrubber
16. Offgas filters
17. Filter pusher
18. Glass drain
19. Needle-valve shutoff
20. Glass collection drum
21. Alkaline quench tower
22. Limestone bed
23. Fresh makeup cooling water
24. Quench tower sump
25. Quench solution recirculating pump
26. Overflow cooling water to waste water holding tank
27. Offgas demisters
28. Offgas thermometer/thermocouple
29. Offgas pressure tap + pitot tube port
30. Induced draft fan
31. Stack
32. Waste water holding tank
33. Dump line to metro sanitary sewer

descriptions and drawings are provided in the test plan (Kelly 1995). Two screw chargers, the simulant blending tank and injection system, and the offgas system were fabricated for Phase 1 testing.

4.3.2.2 Glass Formulation. PEI performed a series of crucible melts to determine the optimum glass formulation. Crucible melts using $NaNO_3$ for 80% of the soda and $NaCO_3$ for 20% of the soda, and powdered sugar reductant in the amount of 35% to 45% of the NO_3^- weight, produced amber (slightly reduced) glasses with 25% waste oxide loading that were easily melted at ~1316 °C. The glass compositions melted were soda-calcia-alumina-silica glasses similar to commercial container glass compositions enriched in soda and alumina. The glasses did not contain B, but did contain 1% Fe_2O_3 as a redox buffer. Determining the reductant addition to achieve a slightly reduced amber glass was considered a key factor for prolonged electrode life. PEI said that it is common for commercial glass melters to show little or no wear on molybdenum electrodes after 2 or more years of melting amber bottle glass. The Phase 1 PEI target glass formulation and batch material proportions developed for the test plan are presented in Table 4-6. The target 10*M* Na DSSF simulant composition was assumed.

Table 4-6. Test Plan Batch Formulation for 100 kg of Glass.

Batch material	Weight (kg)	Oxide	Oxide weight (kg)	Weight in glass (kg)
Low-level waste simulant (1.43 kg/L)	86.81	Na_2O	18.82	18.82
		K_2O	1.43	1.43
		Al_2O_3	3.18	6.00
		Other	1.60	1.60
Limestone	16.77	CaO	9.40	9.77
Floor dry	34.85	Al_2O_3	2.82	--
		Fe_2O_3	1.00	1.00
		CaO	0.37	--
		MgO	0.13	0.13
		SiO_2	30.53	--
Milled zircon	2.00	ZrO_2	1.34	1.34
		SiO_2	0.66	--
Spruce pine sand	28.72	SiO_2	28.72	59.91
Totals	169.15	--	100.00	100.00

4.3.2.3 Feed Preparation and Melter Feeding. Absorbent glass-former additives were selected to achieve a damp batch without free liquid when mixed with the LLW simulant in the screw chargers. Eagle Pitcher Floor Dry 85 (~90% diatomaceous earth) was used as the source for Al_2O_3 not provided by the LLW and for about one-half of the SiO_2. Adding all the reductant as sugar dissolved in the liquid LLW resulted in a feed that was considered too wet, so about one-half of the organic reductant was added as cornmeal with the dry glass-former batch materials. Feed consistency was further optimized using finer particle size grades for about one-half of the floor dry and limestone materials. The resulting floor dry addition was slightly richer in Al_2O_3 than assumed for the batch recipe developed for the test plan. Therefore, the floor dry-to-sand ratio was adjusted slightly for the actual feed batching to achieve the correct target glass composition. The final dry glass-former batch recipe and LLW simulant to dry glass-former mix proportions chosen for Phase 1 testing are presented in Table 4-7.

4.3.2.4 Test Monitoring and Sampling. Samples were taken of the simulant and each raw material lot. After reaching steady-state operation, periodic samples were to be taken of the feed as discharged from the screw chargers, of glass collected from the pour drain, and of the offgas scrubber/quench solution. Scrubber/quench solution samples were to be collected from the blowdown tank where condensate overflow from the scrubber solution tank was collected. The collected blowdown solution volume and time were to be noted and the collection tank emptied following each sampling.

Offgas measurements were to be performed by AmTest Air Quality, Inc. of Preston, Washington, using standard EPA methods. Gas and particulate samplings were planned from the melter plenum and from the offgas duct between the ceramic fiber filter alcove and the quench tower. Modified Method 5 was planned for particulate multiple metals, Method 6C for SO_2, Method 7E for NO_x,

Table 4-7. Final Melter Feed Batch Recipe.

Batch material	Weight (kg) for 100 kg of glass
Liquid waste stream	
Low-level waste simulant	87.37[a]
Sugar	4.08
Dry glass-former mix	
Limestone	17.02[b]
Floor dry	31.90[b]
Milled zircon	1.97
Lane Mountain sand	31.60
Cornmeal	4.03

[a]61.1 L, 64.8 L with sugar added.
[b]A 50/50 blend of coarse and fine particle size grades.

and Method 10 for CO. It was anticipated that little particulate would pass the ceramic fiber filters so the filter pads were to be retrieved while they were pushed into the melter to measure weight gain and sample the collected particulate material.

Other run parameters to be manually recorded in a logbook included the following: melter power (every 30 minutes); melter plenum and filter alcove temperature and pressure (every 15 minutes); and glass melt temperature, electrode holder temperatures, drain temperature, and glass depth (every 30 minutes).

4.3.2.5 Test Chronology Summary. As a result of test preparation delays and surveillance concerns, WHC performed a 'readiness review' at PEI on December 30, 1994. Following this readiness review, WHC issued a 'CURE' notice on January 5, 1995, and scheduled a second readiness review for January 17.

Week of January 16, 1995--As a result of the January 17 readiness review, PEI was judged to have made sufficient progress on surveillance concerns and test preparations to proceed with Phase 1 testing. The melter was started on about January 18 using a cullet and carbonate-based batch formulated to the target glass composition. The melter was heated to ~565 °C using silicon carbide glow-bars. The glow-bars were removed, carbon-arc electrodes inserted, and an arc established. The carbon-arc power supply was insufficient to bring the melter to operating temperature and the use of the carbon-arc electrodes was abandoned. The glow-bars were re-inserted and trails of caustic soda laid down between the electrodes to establish conductivity. After the melter electrodes started firing, additional cullet and carbonate-based batch was fed to increase the glass level in the melter.

Following startup, the melter was idled in a hot-hold condition and calibration work with the feed chargers commenced. Westinghouse Hanford Company technical personnel and sample control specialists arrived at PEI on January 20.

January 22, 1995--Melter operation with manual feeding of the cullet and carbonate-based batch was to be started before the DSSF simulant batched feed was fed through the screw chargers. Glass flow was initiated from center sidewall drain B, which was operated for a short time and then stopped by inserting a steel rod into the drain orifice. When restart of drain B was later attempted, the rod had become welded in the drain and could not be removed. Heat was applied to drain A from which glass discharge was established during the evening. Drain A was stopped with plans to begin feeding the DSSF simulant-based feed through the screw chargers the next morning.

January 23, 1995--Drain A was briefly started at ~0130 and glass discharged for ~5 minutes. Turning off the drain power did not appear to reduce glass flow and a steel plug was inserted into the drain for ~5 minutes and then removed to stop flow. At 0800, 23 kg of the carbonate batch feed were charged to the melter. A 91-kg batch of the dry feed glass-former mix was prepared and four barrels of the Lot 1 DSSF were mixed with powdered sugar reductant additive in the simulant blending tank during the morning. When power was applied to the drain A heating element, it was found to be

nonconductive and was abandoned. Heating of the last sidewall drain carbon was started during the afternoon and glass flow from this drain was established at 1735. A decision was made to maintain continuous glass discharging through the night melting manually charged carbonate batch and feeding the DSSF simulant and glass-former mix in the morning. At 2000, the melter temperature was 1320 °C and three glass pull rates were measured at 18.3 kg/h.

January 24, 1995--During the night and early morning, the temperature was held at ~1320 °C and pull rate measurements ranged from 12 to 23 kg/h. Feeding of the DSSF simulant and glass-former mix using a single screw charger was started at 1135. The sidewall drain carbon element failed at 1216. The bottom drain was started at 1315, stopped at 1400, and restarted at 1500. The AmTest Air Quality Inc. personnel arrived early in the afternoon to set up for offgas measurements to be taken on January 25 and the morning of January 26. The seized rod was removed from drain B using a 'puller' at 1530. Use of the bottom drain continued at a pull rate of ~20 kg/h.

At ~1700 the simulant pump delivery rate was variable and hourly measurements of the level in the simulant feed tank were initiated to monitor simulant delivery rate to the feed charger. By 2000, pull rates had increased to ~40 kg/h and control of the bottom drain was lost at ~2200. The glass discharge was stopped with a water lance. The batch blanket had significantly collapsed and unmelted batch had discharged with the glass before the drain was frozen. An estimated one-third to one-half of the tank glass inventory had drained. Feed was changed over to carbonate batch to reestablish the glass level with known composition feed.

January 25, 1995--Power was applied to start drain B at about midnight. Glass began to flow around the outside of drain B between the drain and the refractory and drain B failed. The glass leakage was stopped with water. Drain B apparently had been damaged and loosened during pulling of the steel rod plug that had been seized in the drain.

A melt foaming incident began at ~0200. The foaming was likely a result of attempting to increase the temperature of glass submerged under fresh carbonate batch that was incompletely melted and equilibrated to a lower temperature. Soda ash was charged to the melter at 0600 to bring the foaming under control. Discharge from the bottom drain was reestablished at 0816. Control of the bottom drain was lost at 0846, again discharging a significant portion of the glass inventory before the drain could be frozen with a water lance. Further Phase 1 testing activities were terminated and the Spectrum Glass crew dismissed. AmTest Air Quality Inc. personnel indicated that it likely would be several weeks before they would be available to attempt completion of the offgas measurements.

4.3.3 Results and Observations

4.3.3.1 Feed Charger Performance. The screw chargers ran at a constant rate fixed by drive motor speed and the drive sprocket ratios. Screw charger delivery rates were to be controlled by percent time-on timers. The liquid LLW simulant delivery rate was controlled by an 'adjustable' air-driven double diaphragm pump. A solenoid valve routed the liquid stream either to the screw

charger or back to the agitated simulant feed tank. The liquid stream was directed to the screw charger only when the screw charger was on and exceeded the delivery rate required for the target composition requiring a shorter 'on time' for the liquid stream than for the screw charger. A ratio of ~7 seconds on for the screw charger and 3 seconds on for the liquid feed was expected to give the proper batch composition based on calibration trials.

Concerns regarding the ability to accurately control feed composition and uniformity were expressed by technical participants who recommended modifications such as a peristaltic or motor-driven variable displacement pump for the liquid stream and variable-speed control for the screw chargers. However, Mr. Penberthy did not accept the recommendations to modify the feed delivery control system. Instantaneous variability of the feed composition exiting the screw charger was a particular concern because it would not be possible to collect representative feed samples needed to provide data for melter mass balance evaluation. The use of more sophisticated metering control of the liquid LLW and dry glass-former feed streams will likely be required to ensure process control for an actual production facility.

Only one of the two screw chargers was used during the melter demonstration testing. During calibration and testing of the screw chargers, it became apparent that the chargers were too short to allow uniform mixing of dry and liquid components before exiting the multiple ports in the charger barrels, with much of the dry batch exiting the first ports. The ports before the end of the charger barrel were then closed so feed would exit only through the end of the charger barrel. To prevent batch pile buildup, the batch was manually leveled across the melter surface. The use of longer screw chargers in a full-scale system may allow for multiple drop points and improved batch distribution. However, controlling batch distribution in a remote process using fixed-position screw chargers with multiple drop points will likely require a significant development and demonstration effort.

4.3.3.2 Batch Blanket Characteristics. A batch blanket that was several inches thick was established at ~1200 on January 24. Feeding the DSSF simulant and absorbent glass-former additives through a single charger was continued until control of the bottom drain was lost ~10 hours later. The batch blanket was easily leveled by periodic raking with the material spreading as damp clumps. The batch blanket was essentially quiescent, with no signs of bridging or bubbling. Periodic flames of 1 to 2 seconds duration were observed venting from the batch blanket and a slight odor of NO_x was detectable on the melter deck. Another odor during vitrification of the mix-in-the-charger feed was that of baking cornbread.

4.3.3.3 Melt Rates. PEI expected the melt rate with the damp mix-in-the-charger feed to be ~80 to 90 $kg/m^2/h$ glass production (Kelly 1995). Glass pull rates recorded over a period of several hours on January 24 before loss of drain control suggest melt rates were on the order of ~40 $kg/m^2/h$.

4.3.3.4 Test Sample Characterization. Samples to be taken under hopefully steady-state operating conditions during January 25-26 when offgas measurements were to be made were to be the basis for evaluating melter performance, process control, and melter mass balance. A few feed samples from the feed charger discharge and glass samples from the bottom drain were taken during the DSSF simulant feeding period on January 25 and have been

retained as archives by WHC. Because of the feed calibration control and drain and melter operation problems, WHC personnel believed that these samples were not representative of steady-state operation and they were not sent to contract laboratories for analysis. The glass samples were clear, light green to amber in color, and appeared to be homogeneous and well reacted.

4.3.3.5 Volatility and Melter Mass Balance. Had it been possible to obtain homogeneous and uniform feed samples and offgas samples over an extended period of steady-state operation with full cold-top batch coverage, it is expected that low volatility loss and good mass balance results would have been obtained. With the possible exception of halides, which may have a higher volatility with damp feed, the mass balance results measured in the Envitco dry feed test would likely be applicable to the PEI technology.

4.3.4 Termination of Testing

On January 27, 1995, representatives from RL, WHC Procurement, and the WHC LLW Program Office met with WHC technical personnel at WHC to discuss continuation of testing at PEI. The group decided to direct PEI to pursue a safe and orderly shutdown of Phase 1 testing activities. This decision was based primarily on considerations related to PEI's viability as an organization capable of completing the technical objectives of the LLW Melter Vendor Testing Program, and is not a reflection on the technical merits of the PEI-proposed LLW vitrification concepts. A few of the considerations leading to this decision are as follows.

As a result of inefficient test preparation and delays, most of the funding negotiated and allocated for the testing at PEI had been spent. PEI was in Chapter 11 bankruptcy following the loss of a lawsuit in September 1994. The group believed that significant additional time and funds would be required to upgrade the melter system to meet the technical objectives of Phase 1 testing. A redesigned, reliable, and controllable melter drain system appeared to be required. Significant upgrading of the feed metering and control systems for the mix-in-the-charger feed was needed. The offgas blower was undersized and would need to be upgraded. General upgrading of test instrumentation also would be desirable to gather the data needed to meet Phase 1 technical objectives. PEI was the only Phase 1 vendor not to use computer-automated data logging. Operational safety concerns also were expressed. Another central concern was the commitment of key technical personnel supporting PEI who had other full-time jobs. By 1994, when the Hanford Site LLW Melter Vendor Testing Program was initiated, the only remaining full-time employees at PEI were Mr. Penberthy and his secretary. Former PEI employees and personnel from Spectrum Glass of Woodinville, Washington, provided part-time support to PEI to perform Phase 1 testing activities.

4.4 DURATEK

Duratek of Columbia, Maryland, provides vitrification technology to treat radioactive and hazardous waste materials. The VSL-CUA in Washington, D.C.,

performs vitrification research and development for Duratek. Phase 1 testing was performed in Duratek bench- and pilot-scale melter systems at VSL-CUA. The Duratek Phase 1 testing was performed under WHC contract MMI-SVV-384315.

4.4.1 Melter Technology Description

The Duratek melter technology is a Joule-heated, ceramic, refractory-walled melter with Inconel plate electrodes. Bubblers are used to increase mixing within the melt, effectively increasing the processing rate. The glass melt exits the melters via an airlift-assisted overflow drain. Although slurry feeding has been used in waste vitrification demonstrations, it may be possible to feed dry glass-forming material and liquid waste to the melter separately.

4.4.1.1 Full-Scale Concept. The Duratek-proposed technology for a 200 tonne/day LLW vitrification facility incorporates three DuraMelter 67-k (67 tonne/day) melter systems. Each melter would have its own dedicated feed preparation system and offgas system.

Duratek considers the design and configuration of the proposed full-scale melter to be proprietary. The full-scale melter would be similar to the melters tested during Phase 1 in that it would have ceramic refractory walls, be heated using Inconel electrodes, and use bubbling to increase processing rates and aid in mixing. The configuration of the full-scale melter, although not demonstrated during Phase 1 testing, would be very similar to the Duratek melter being built for the vitrification of M-Area wastes at the Savannah River Site (SRS). The design of the full-scale melter is based on a production rate of 3 tonne/m^2/day (125 kg/m^2/h), giving an approximate surface area of 22 m^2.

4.4.1.2 Technical Issues. A few key issues need to be considered for the Duratek technology.

Processing Rate--The maximum processing rate that can be accomplished with this technology must be determined. The full-scale melter is based on a processing rate of 125 kg/m^2/h, but processing rates in demonstrations have not yet reached this value. Average glass melting rate for the steady-state portion of Phase 1 testing in the pilot-scale DM-1000 melter was 67 kg/m^2/h. More importantly, the effects of increased processing rates on other parts of the melter system, such as melter life, partitioning of components to the offgas system, and glass quality, must be analyzed to determine the optimal processing rate for this technology. In conjunction with the processing rate, the partitioning of radioactive elements between the glass and the offgas system also must be evaluated.

Feed System--The simplest and most economical and reliable feed system for this technology must be determined. Although slurry feeding was successfully demonstrated during Phase 1, there may be advantages (simplified radioactive feed processing) to feeding the liquid LLW to the melter separately from the dry glass-forming additives. The issue of whether proper mixing and compositional control can be achieved using this feed method must be determined.

Electrodes--The proprietary design and configuration of the Inconel electrodes in the full-scale melter have not been demonstrated. It is assumed that, as with the smaller-scale melters, the electrodes in the full-scale melter could not be replaced and would have to last the lifetime of the melter. However, this electrode design is to be demonstrated by Duratek in the vitrification of SRS M-Area wastes scheduled to begin in 1996.

4.4.2 Phase 1 Testing

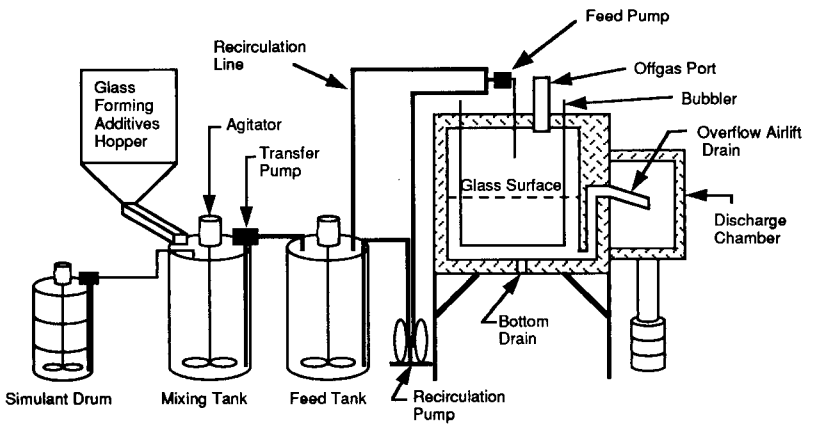
Phase 1 testing was performed by Duratek with its partner, the VSL-CUA, acting as a subcontractor. All testing was performed at the VSL-CUA by personnel from the VSL-CUA and Duratek. Testing was performed according to the vendor-prepared test plan which was released by WHC (WHC-SD-WM-VI-020 [Eaton 1995a]). Parsons Engineering Science, Inc. (PES) of Fairfax, Virginia, conducted offgas sampling and monitoring in conjunction with personnel from VSL-CUA. Additional testing details are provided in the Duratek Phase 1 testing report (WHC-SD-WM-VI-027 [Eaton 1995b]).

Two melters were used for Phase 1 testing. The first stage of Phase 1 testing was performed in the radioactive bench-scale DM-100 melter (100 kg/day glass nominal capacity) between September 21 and September 28, 1994. This stage of testing consisted of a 3-day turnover period followed by 3 days of steady-state testing. A turnover period is defined as a period of time during which the target feed composition is processed to flush the melter and convert the glass inventory and product glass to the desired target composition. During the DM-100 run, approximately three melter inventories were processed in the turnover period and in the following steady-state portion of the run.

The second stage of testing was performed in the pilot-scale DM-1000 melter (1,000 kg/day glass nominal capacity) between December 13, 1994, and January 21, 1995. In this stage of testing, the turnover period was divided into three distinct parts. The first part (December 13-15, 1994) was used to 'shake down' the new feed system. The second part (December 17-20, 1994) was used to more carefully study the use of reductant in the feed and H_2O_2 spraying in the scrubber to reduce the NO_x concentrations in the offgas. Although a feed reductant had been successfully used in the DM-100 run to reduce conversion of feed nitrates and nitrites to NO_x, more work was required to determine the reductant concentration and melter conditions that produced the best results. The third part (January 12-15, 1995) was used to complete the compositional turnover and prepare the system for the steady-state portion of the test. The DM-1000 steady-state run segment (January 19-21, 1995) only processed approximately two melter volumes of glass because it was believed that the test objectives could be met in this amount of time and that additional run time would significantly increase costs without providing much additional data.

4.4.2.1 Test Facilities. The DM-100 melter was originally used to test the Fernald vitrification system and is equipped with a liquid feed system enclosed in a glovebox to be used for radioactive materials. For Phase 1 testing, a new liquid feed system was installed to avoid contamination and simplify feed preparation. A schematic drawing showing general features of Duratek test melters is provided in Figure 4-6. The slurry feed configuration shown is that used with the DM-1000 melter.

Figure 4-6. Schematic Drawing Showing General Features of the DuraMelter Test Systems. The slurry feed system shown is that used with the DuraMelter-1000.



The melt pool in the DM-100 is contained within a fused-cast refractory and has Inconel plate electrodes on two opposite sides. The melt surface area is ~35.6 by 35.6 cm with a typical melt inventory of ~100 kg. The glass melt is poured from the melter via an overflow-type drain equipped with an air lance to provide control of pouring. The plenum and the discharge chamber are equipped with sheathed resistance heaters. The DM-100 test melter at VSL-CUA is enclosed in a glovebox to allow testing with actual radioactive feeds.

The DM-1000 melter was designed for vitrification of asbestos wastes and equipped with a solids feed chute. Based on the success in the smaller melter, a slurry feed system was designed and assembled for the DM-1000. The DM-1000 is similar in design to the DM-100, but is larger, has a proportionally deeper melt pool, and uses upper and lower sets of electrodes. The melt pool surface area is 107 by 107 cm and the melter holds ~2,700 kg of glass.

4.4.2.2 Feed Preparation and Glass Formulation. The feed system for the DM-100 consisted of a mixing tank (55-gal [208-L] drum) equipped with an agitator and a recirculation/transfer pump, a feed tank (55-gal [208-L] drum) also equipped with an agitator and recirculation loop, and a peristaltic feed pump and single water-cooled feed nozzle in the center of the top of the melter. To prepare a batch of feed, the requisite amount of DSSF simulant was transferred to the mixing tank and a preweighed batch of dry additives was placed in the hopper of a vibratory feeder and gradually added to the simulant in the mixing tank. After the feed was fully mixed, it was transferred to the

feed tank to allow constant feeding of the melter while the next batch was being prepared. During the steady-state portion of the run, 250 g of urea were added per liter of feed to reduce NO_x production in the melter.

The feed system for the DM-1000 was functionally the same as the smaller DM-100 feed system. The larger DM-1000 system used two 1,900-L tanks, and instead of a vibratory feeder, employed a screw feeder to convey the dry glass-former additives from a closed hopper to the mixing tank. During the DM-1000 steady-state run, only 66 g of urea were added per liter of feed. As with the smaller DM-100 system, a recirculation loop carried the feed to the top of the melter, but the DM-1000 was equipped with two peristaltic feed pumps and two water-cooled feed nozzles to provide feed on both sides of the bubbler. These feed nozzles also had a mechanical auger to prevent plugging.

Duratek chose to develop its own glass formulation for Phase 1 testing according to the requirements in the SOW (Wilson 1994). Table 4-8 shows the batch formulation based on the batch logbook from the DM-100 run. The Table 4-8 batch formulation was essentially scaled up for the DM-1000 testing.

4.4.2.3 Test Monitoring and Sampling. Critical parameters, such as temperature, pressure, and current/voltage, were continuously monitored and recorded on a computer-based logging system for each melter system. Manual measurements, such as the feed level in the feed tanks, were recorded in the

Table 4-8. Duratek, Inc. Batch Formulation (DuraMelter-100 Test).

Batch material	Weight (kg)	Oxide	Oxide weight (kg)	Weight in glass (kg)
Low-level waste double-shell slurry feed simulant (61.13 L, 1.42 kg/L)	86.8	Na_2O	18.95	18.95
		K_2O	1.44	3.68
		Al_2O_3	3.18	6.17
		Other	1.62	1.62
Pechiney, Al_2O_3	2.99	Al_2O_3	2.99	--
US Borax, H_3BO_3	10.89	B_2O_3	6.13	6.13
Minerals Tech., $CaCO_3$	13.89	CaO	7.78	7.78
NOAH, Fe_2O_3	7.47	Fe_2O_3	7.47	7.47
Armond, K_2CO_3	3.29	K_2O	2.24	--
US Silica, SiO_2	39.65	SiO_2	39.65	42.13
RGC Minerals, TiO_2	0.99	TiO_2	0.99	0.99
RGC Minerals, $ZrSiO_4$	7.55	ZrO_2	5.08	5.08
		SiO_2	2.48	--
Total	173.52	--	100.00	100.00

operations logbooks. The offgas from the melter was monitored by PES and the VSL-CUA at the exit point from the melters and at other points farther down the offgas system.

During the DM-100 steady-state run, samples of the DSSF simulant and glass-former additives were taken before the run, and samples of feed, glass, scrubber, and quencher liquids were taken every 4 hours and every time an offgas particulate sample was completed. The baghouse was sampled at the beginning and end of the steady-state portion of the run, and the surface of the melt pool was sampled at the end of the run. A special melter material coupon assembly was installed in the melter for the duration of the steady-state run. This assembly included Inconel 690 and 601, and K-3 and Zirmul* refractory. The coupon assembly was used to obtain corrosion information on the various melter materials because it was not possible to rebuild the melter with fresh materials before the Phase 1 test, or to dissect it after the test. The coupon assembly was designed to hang down from the roof of the melter into the melt pool so that the materials would be in contact with the melt, cold cap, and plenum atmosphere.

During the DM-1000 steady-state run, samples were taken at longer time intervals due to experience gained from the smaller-scale DM-100 test. The feed was sampled only once per batch, and the glass was sampled approximately every 4 hours and whenever an offgas particulate measurement was completed. The scrubber was sampled every time solution was transferred to a blowdown tank so an accurate estimate could be made of the components removed from the offgas. The baghouse catch was sampled every time a baghouse was reconditioned with fresh, diatomaceous earth and at the end of the run. The filter cake and backwash water from the scrubber solution filter were sampled at the end of the run.

Additional details on the sampling positions and procedures for the DM-100 and DM-1000 tests are provided in the test plan (WHC-SD-WM-VI-020 [Eaton 1995a]) and in the Duratek Phase 1 test report (WHC-SD-WM-VI-027 [Eaton 1995b]).

4.4.2.4 Test Chronology. Detailed test chronologies are presented in WHC-SD-WM-VI-027. The following highlights and significant events are from both Phase 1 runs.

4.4.2.4.1 DM-100. The DM-100 testing consisted of a turnover period during which radioactive Fernald glass was flushed from the melter, and a 'steady-state' period during which Phase 1 test data were obtained. Various feed reductant and operating parameters were tested during the turnover period to determine optimum conditions for the steady-state run segment.

September 21, 1994--The turnover run started at 1735 (time 0), a glass sample was taken, slurry feeding started at 2042, and an initial sample set (feed, scrubber, quencher and glass) was taken at 2100.

September 22, 1994--Melter feeding was stopped from 0340 to 1635. At 1042, H_2O_2 was added to the offgas scrubber solution to test its effect on

*Zirmul is a trademark of North American Refractories Company.

reducing NO_x, which resulted in a foaming event in the scrubber and leakage of solution from the scrubber. Scrubber and quencher solutions were further adjusted with H_2O_2 and NaOH additions, and additional test samples were taken during the afternoon and evening.

September 23, 1994--Urea was added to the feed tank between 0125 and 0150 to test its effectiveness as a reductant additive for reducing melter NO_x production. Starch was added to the feed at 1220 to test its effectiveness as a reductant additive for reducing melter NO_x production. The feed containing starch gradually became difficult to pump even with the addition of water to the feed.

September 24, 1994--Returned to urea reductant feed and continued turnover melter operation with periodic sampling. The feed rate was gradually increased to ~200 mL/min. The DM-100 turnover run segment was completed at 1450 having produced 304 kg of glass.

September 26, 1994--The K-3 and Zirmul refractory test coupons were placed in the melter at ~1000. The steady-state test start (time 0) occurred at 1342 with slurry feeding starting at 1412 at a rate of 190 mL/min. A mound of dry feed built up below the feed tube. Bridging of the cold cap had apparently occurred allowing the melt level to fall below the cold cap when pouring glass resulting in loss of heat transfer from the melt to the cold cap. Air bubbling rate was increased to 80 $stdft^3/h$ and feeding was stopped until the mound was melted. Feeding was resumed and bubbling reduced to 16 $stdft^3/h$ at ~1930. More frequent glass pouring (less draw-down in melt level) with increased bubbling was planned to prevent further cold-cap bridging and feed mound buildup. Two Method 5 offgas particulate samples were taken and two CEM runs at four locations each were made for NO_x, SO_2, total hydrocarbon (THC), CO, and O_2 by PES.

September 27, 1994--Increased pressure drop across the quencher was noted and water was sprayed into the melter to the quencher transition line at 0720 to clean out deposits using a spray nozzle installed for this purpose. Deposits were also cleaned from the film cooler and initial portion of the transition line. One Method 5 offgas particulate sample was taken and two CEM runs were made by PES.

September 28, 1994--The steady-state DM-100 run segment was completed at 0445 having produced 304 kg of glass.

4.4.2.4.2 DM-1000. The DM-1000 testing also consisted of a turnover period during which time glass from asbestos vitrification testing was flushed from the melter, and a steady-state period during which Phase 1 test data were obtained. Various offgas treatment and operating parameters were tested during the turnover period to determine optimum conditions for the steady-state run segment.

December 13-16, 1994--The first portion of the DM-1000 turnover run started at 1313 on December 13. During this portion, the feeding was started and stopped several times to make adjustments to the feed and offgas systems. Feed rates between 0.76 and 2.66 L/min were achieved using the two new

metering pumps. At 2000 on December 15, the metering pumps were replaced with two peristaltic pumps capable of pumping 2 L/min with both pumps. Approximately 861 kg of glass were poured from the melter during this portion of the turnover run.

December 17-20, 1994--The second portion of the turnover run started at 1600 on December 17 and was dedicated to more detailed testing of NO_x reduction. The feed rate was varied between ~1 and 2 L/min of diluted feed. The Hanford Site melter feed was diluted by ~3 times (NO_3^-/water similar to SRS M-Area feed) so that data could be used for the M-Area Project. Additional details on NO_x reduction are presented in WHC-SD-WM-VI-027. During the second portion of the turnover period, 2,983 kg of glass were produced. The melter was idled at reduced power during the Christmas through New Years holiday period.

January 12-15, 1995--The third portion of the turnover period started at 1835 on January 12, 1995, with a feed rate of 2 L/min. Filters were added to filter the solution in the scrubber sump to remedy the problem of precipitated or carryover solids found in the scrubber sump earlier in the turnover run. The filters used diatomaceous earth as a filtering media. During the third portion of the turnover run, 3,250 kg of glass were produced.

January 19-21, 1995--The steady-state portion of the DM-1000 started at 0700 on January 19, 1995, with a feed rate of 1.8 L/min. After ~30 minutes of feeding, the cold cap covered ~50% of the melt surface. After several hours of feeding, and throughout most of the run, the cold cap covered ~80% to 90% plus of the melt surface. At 0125 on January 20, the rotating mechanism on augered feed tube No. 2 wore out so feed to that tube was stopped; the feed rate through feed tube No. 1 was increased to compensate for the lack of feed to feed tube No. 2. Feed tube No. 2 was repaired and started again at 0306 on January 20. Feed tube No. 2 was later replaced with a spare, and at 0630 on January 20, the drive mechanism for feed tube No. 1 was replaced and brought back online by 0720. After several more outages, the drive mechanisms were slightly reconfigured so the feed tubes ran smoothly for the rest of the run. At 1705 on January 20, after tripping the emergency offgas vent, the film cooler was inspected and deposits were found to be building up on the duct. The deposits were dislodged back into the melter. Two Method 5 offgas particulate samples were taken and two CEM runs at three locations each were made for NO_x, SO_2, THC, CO, and O_2 by PES on January 19. An additional Method 5 sample and additional CEM runs were made by PES on January 20. The steady-state DM-1000 run segment was completed at 0800 on January 21 having produced ~3,700 kg of glass.

4.4.3 Results and Observations

In general, the demonstrations in both the DM-100 and DM-1000 systems went quite smoothly. The melter feed, a mixture of DSSF simulant and glass-forming additives, displayed better than expected rheological properties. The melters appeared to process the feed with ease, and achieved processing rates approximately double the nominal design rates of 100 and 1,000 kg/day glass. The glass product was relatively homogeneous and durable, and offgases were within the expected range.

Results from the small-scale test indicated that the addition of urea to the feed caused a significant reduction in the NO_x exiting the melter. In addition, urea improved the rheological properties of the melter feed in contrast to the addition of starch, which made the feed difficult to pump. During the second turnover period of the DM-1000 testing, experiments were performed to determine the best ratio of urea to nitrogen in the feed. Effective decomposition of the NO_3^-/NO_2^- was achieved with as little as 66 g of urea per liter of feed.

High processing rates were achieved in both melters compared to previously processed feeds. This may have been due in part to the high solids content of the melter feed made only from the 10 mol Na DSSF simulant and glass-forming additives without additional water, and/or due to the high flux content of the melter feed. The average processing rate throughout the 40 hours of steady-state operation in the DM-100 was ~60 $kg/m^2/h$, with periods of up to 5 hours processing at ~100 $kg/m^2/h$. The temperature was maintained at ~1160 °C with a power input of ~20 kW. The plenum temperature was kept at ~700 °C throughout the run. The average processing rate in the DM-1000 during the ~48 hours of steady-state operation was ~67 $kg/m^2/h$, with some periods of stable operation at ~75 $kg/m^2/h$. The glass temperature was maintained at ~1130 °C with a power input of ~120 kW and the plenum temperature at ~700 °C. These rates represent the comfortable processing rates chosen for the steady-state portion of the demonstrations. The operators were instructed to not push the melters to their limit in terms of processing rate but instead to choose a rate at which they could be confident that few processing upsets would occur. Higher processing rates are likely to be achievable but have not been demonstrated thus far.

The feed entrainment loss (feed material carried directly to the offgas system without being incorporated in the melt) was determined to be no greater than 0.6%. This value was calculated using the amount of certain components found in the offgas system and known to not have significant volatility from the melt. In general, the volatility of components from the melt during processing was greater than that of a true cold-top melter in which none of the melt surface is exposed, but less than that of hot top or exposed surface melters. Although the use of vigorous bubbling increases the processing rates per unit melt surface area, it is also expected to increase the exposed glass from which volatile components can escape. Overall, the product glasses were close in composition to the target. Section 6.0 provides a more detailed discussion of volatility and mass balance across the melter.

The few problems experienced during the demonstrations did not seem to reflect any significant or inherent deficiency in the technology but were more related to the specific test systems, the scale of the test systems, or the fact that this was the first time some of the equipment had been operated with this kind of feed. A problem that should not be minimized was the buildup of material in the offgas ports, which was experienced in both test runs. This is a common problem in waste melters and must be carefully examined. Although the occurrences of material buildup in the tests may have been caused by non-ideal offgas port geometry, or air inleakage due to offgas sampling, the potential for this problem is apparent in that enough material is leaving the melter through the offgas port to cause a buildup.

More detailed discussions of Phase 1 testing results at Duratek are presented in WHC-SD-WM-VI-027. A summary of the offgas monitoring and sampling performed by PES, as well as the field data from the DM-100 run, is contained in WHC-SD-WM-VI-028 (Eaton 1995c) and from the DM-1000 run in WHC-SD-WM-VI-029 (Eaton 1995d).

4.5 USBM

The USBM performed Phase 1 testing at its Albany Research Center in Albany, Oregon. The thermal waste treatment facility at the Albany Research Center was constructed and has been supported through the collaboration of various contributors. During the last several years, the Idaho National Engineering Laboratory (INEL) has conducted waste thermal treatment development testing at the facility and has funded significant upgrades to the pilot-scale carbon electrode melter system and supporting equipment. Phase 1 testing was made possible at the USBM in part through the cooperation between INEL and WHC, and was performed under WHC contract MMI-SVV-384216.

4.5.1 Melter Technology Description

The USBM technology is based on the 3-phase electric arc furnace commonly used in the metals industry. The general furnace design is referred to in the literature and industrial practice by various names, including electric arc furnace, carbon arc furnace, electric arc melter, and carbon electrode melter. In this report, the name carbon electrode melter is used because this term most accurately describes the important features of this technology for vitrification of Hanford Site wastes.

The melter uses top-entering vertical carbon electrodes and may be operated in a higher voltage regime where most of the heat is supplied to the melt as radiant heat from arcing at the melt surface, or with the electrodes submerged in the melt and operating at lower voltage, in which case most of the heat occurs as a result of Joule heating. The melter is water cooled and uses only a thin layer of ceramic refractory to protect the melter shell in glass contact areas. Once in operation, a frozen glass skull layer is formed between the refractory liner and the melt providing a barrier to erosion of the refractory and melter shell by the glass melt.

The melter generally operates using dried feed materials to avoid the reaction between water and the carbon electrodes, although there is some capacity to handle moisture. The USBM developed two feed drying and reacting processes to prepare prereacted dry feed for Phase 1 testing. The Type A feed is prepared by pelletizing high-surface area glass-forming materials and combining the pellets with the liquid waste (simulant) which is absorbed by the pellets. The Type B feed is prepared by mixing the glass-forming materials with the liquid waste before pelletizing. In both feed processes, the feed is dried and reductant additives reacted with feed NO_3^-/NO_2^- before being fed to the melter.

4.5.1.1 Full-Scale Concept. The USBM-proposed technology for a 200 tonne/day LLW vitrification facility incorporates two 100 tonne/day glass melters. Each melter would have its own feed delivery system and offgas system, but the feed for both melters would be prepared in a single process line.

The full-scale melter would be different from the carbon electrode melter tested during Phase 1 in terms of configuration, but would use many of the concepts tested during Phase 1. The melter would consist of a water-cooled shell lined with a thin layer of refractory. A skull layer of solidified glass provides protection of the refractory and melter shell in glass contact areas and is expected to result in extended melter life. The melter would be powered by three large, vertical carbon electrodes configured in-line down the center of the melter. Pelletized feed would be distributed by multiple feed ports on both sides of each electrode. The melt would be poured from multiple drains located along one side of the melter. To allow cold restart of the melter following shutdown, conductive material such as crushed graphite would be fed through ports to create conductive paths between the electrodes.

To process 100 tonne of glass a day, the carbon electrodes will have to be ~71 cm in diameter. The USBM suggests using self-baking electrodes. This process requires electrode processing facilities above the melter in which raw materials are mixed, extruded, and baked continuously while they are slowly fed into the melter containment cell and into the melter. This self-baking process would be housed in a nonradioactive environment above the melter cell. The electrical connections also could be made outside the cell. An alternative would be to remotely add pre-made carbon electrode sections in the melter cell as needed. This alternative would require a facility with an overhead crane for remote operations in the melter cell.

Based on conservative melting rates achieved during the Phase 1 testing (~220 $kg/m^2/h$), a 100 tonne/day melter would require a melt surface area of ~19 m^2. This would result in overall dimensions of 3.3 by 9 by 2.5 m high. If processing rates similar to those achieved during the small-scale scoping tests can be sustained, the surface area of a 100 tonne/day melter could be as small as 14.5 m^2.

4.5.1.2 Technical Issues. A few key technical issues that need to be addressed before implementing the carbon electrode melter technology in the LLW vitrification facility are discussed below.

Feed Processing--An important issue is whether wet unreacted feed can be successfully processed in the melter. During Phase 1 testing, methods for producing a dry, prereacted melter feed were investigated and these feeds were successfully processed in the melter. However, the large size and the mechanical complexity of the equipment required for processing these dry prereacted feeds would likely make these feed alternatives difficult to justify in a full-scale remotely operated radioactive facility. However, if the melter can be modified (sheathed electrodes, etc.) to accept and process damp or wet unreacted feeds, the feed preparation process could be greatly simplified. For example, it may then be possible to mix and charge the feed using a mix-in-the-charger feed system similar to that proposed by PEI.

Electrode Feeding--Another issue is the need to continually or frequently provide additional electrode material to the melter. Feeding additional electrode material to the melter as it is consumed during operation may prove to be a difficult or complicated operation in a remote-maintained environment.

Volatility and Entrainment Losses--Although significant reductions in feed component losses to the offgas system were achieved between runs WHC1 and WHC3, losses were still high relative to those demonstrated for cold-top Joule-heated technologies. Using larger submerged electrodes operating at lower voltage, and an improved drain design more suited for pouring of viscous glass melt, it may be possible to operate with full cold-top batch coverage significantly reducing volatility and entrainment losses. However, full cold-top operation has not been demonstrated and may also result in significantly reduced melting rates if achievable.

Melter Drains--During Phase 1 testing, the glass was tapped through a copper or graphite tube extending through the water-cooled melter shell slightly below the desired melt surface level. This drain configuration works well for low viscosity metals and slag melts, but is not suited for continuous pouring of viscous glass melts. Excessively high melting temperatures were required to maintain continuous drain flow, a problem that was made worse by high Na and B volatility losses caused by the high temperatures which further increased melt viscosity. A glass tapping temperature of ~1600 °C was required to maintain a continuous drain flow during run WHC1 for a target glass formulated to have a melting temperature of 1296 °C at 100 poise viscosity. An overflow or heated drain design is needed that will allow continuous glass pouring at near the target glass design melting temperature.

4.5.1.3 Technology Strengths. The following strengths are identified for the USBM carbon electrode melter technology.

- Maturity of technology--Carbon electrode arc melters have been widely used in industrial applications such as melting specialty metals, melting ceramic refractories, rock wool production, and steel (mini-mills) melting from recycled scrap.
- Compact size--High specific melt rates ranging from 140 to 365 $kg/m^2/h$ were demonstrated in Phase 1 testing compared to 43 to 110 $kg/m^2/h$ demonstrated for Joule-heated melters.
- Flexibility--This melter can melt wastes with a variety of characteristics. The melter is robust and can be easily shut down and restarted.
- This melter can potentially be operated with full cold-top batch coverage to suppress volatility and entrainment losses, and may potentially be capable of melting damp mix-in-the-charger feed.

4.5.2 Phase 1 Testing

Phase 1 testing was performed by the U.S. Department of the Interior, USBM, in the thermal waste treatment facility at the Albany Research Center. Offgas sampling and monitoring were provided by Entropy, Inc. under contract

to INEL for the WHC Phase 1 24-hour melter demonstration test and subsequent INEL tests. The melter feed was prepared by Methods A and B between January 15 and February 16, 1995, onsite at the Albany Research Center. The dried, pre-reacted feed was stored in plastic-lined 55 gal (208-L) drums until needed for melter testing. The Phase 1 24-hour demonstration test referred to as WHC1 was conducted March 8 to 10, 1995, in accordance with the approved test plan (WHC-SD-WM-VI-021 [Eaton 1995e]).

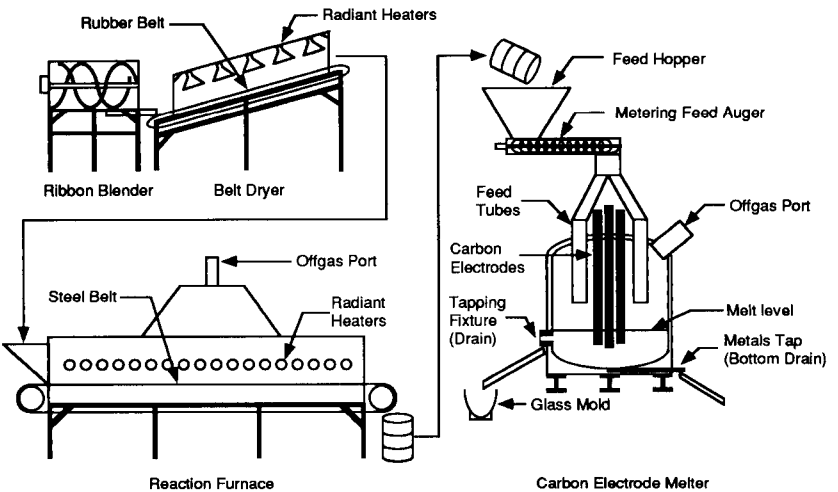
A second test referred to as WHC2 was conducted on April 10, 1995, to address problems that occurred during the WHC1 test, namely the excessively high melting temperatures near the electrodes required to maintain continuous glass pouring and the resulting high volatility and entrainment losses. The main modifications made for the WHC2 test were to alter the power supply to reduce the voltages provided to the melter and to use a graphite tube instead of the water-cooled copper fixture to improve the ability to tap the melter at lower temperatures. Additional adjustments were made in response to offgas system problems that were noted during the WHC1 test. The WHC2 test was performed by the USBM at no additional cost to WHC.

A third test referred to as WHC3 was performed on May 4, 1995, in a further attempt to lower maximum melt temperatures and volatile component losses. Significant changes to the system for the WHC3 test included the addition of larger 20.3-cm (8-in.) diameter electrode stubs to the existing electrodes to reduce current density at the electrode-melt interface, and to again modify the drain as a water-cooled copper fixture fitted with a graphite sleeve so the diameter of the tap hole could be optimized by changing the sleeve. The WHC3 test was performed by the USBM at no additional cost to WHC.

Additional details on the Type A and B feed preparation and melter test runs WHC1, WHC2, and WHC3 are provided in the USBM Phase 1 report (WHC-SD-WM-VI-030 [Eaton 1995f]). Detailed discussion and results on the WHC1 offgas measurements by Entropy, Inc. are provided in the USBM Phase 1 melter offgas report (WHC-SD-WM-VI-032 [Eaton 1995g]).

4.5.2.1 Test Facilities. The melter that was demonstrated for Phase 1 is a sealed 3-phase carbon electrode melter with three 10.16-cm (4 in.) diameter graphite electrodes arranged in an equilateral triangle with ~28.5 cm between electrode centers. The melter consists of a steel shell which is lined with a thin layer of high alumina refractory on the walls and hearth. Water cascades down over the outer shell of the melter cooling the refractory and freezing a glass skull layer on the inner surface of the refractory liner. The bottom of the melter (hearth) is lined with a thicker refractory layer and is cooled only by the ambient atmosphere. The position of the electrodes, which enter the melter through packed seals in the melter roof, can be adjusted during melter operation to control the depth of the electrodes in the melt and compensate for electrode consumption. The feed tubes protrude down through the roof to within 46 cm of the melt surface. The melt surface area is circular and ~1.12 m^2. The melt is poured from the melter through a water-cooled copper tapping fixture (test WHC1). A drain in the bottom of the hearth must be bored out to drain the melter or remove settled sludge or metals from the hearth. A schematic diagram of the USBM test system is shown in Figure 4-7. Additional details regarding the design and construction of the test system are presented in WHC-SD-WM-VI-021 (Eaton 1995e).

Figure 4-7. Schematic Diagram of U.S. Bureau of Mines Test System. (Type B feed preparation shown.)



4.5.2.2 Feed Preparation and Glass Formulation. The USBM chose to use the LD6-5510 glass composition, which was one of the formulations developed by PNNL and pre-approved for use during Phase 1 testing. The two feed types developed by the USBM for Phase 1 testing required that different raw materials be used as the glass-forming additives to obtain the specific properties needed for the preparation processes. However, both feeds provided essentially the same LD6-5510 glass composition. The raw materials and formulation of the two feed types are listed in Tables 4-9 and 4-10.

The raw materials for the Type A feed were mixed together in a double ribbon blender with only a minimal amount of water to reduce dusting. The disc pelletizer used to prepare Type A feed pellets for contacting with simulant was ~1.2 m in diameter and required constant operator attention. The pellets formed by this process were ~0.6 to 1.3 cm in diameter. The pellets were dried overnight in a large oven at 100 °C to remove moisture that was added in mixing and pelletizing. The pellets were partially saturated with the simulated waste in a small cement mixer, dried on a belt dryer (~9.1 m long) with radiant heaters, and reacted in a belt furnace (air temperature ~300 °C, ~12.2 m long).

The mixer used to mix the glass-forming materials with the simulated liquid waste for the Type B feed was a double ribbon blender with 100 ft^3 capacity. The Type B pellets were formed in the mixer by adding the predetermined amount of simulant and additional water and mixing for a short time. The pellets (or agglomerates) were formed by the mixing action in the

Table 4-9. Batch Formulation, Type A Feed.

Batch material	Weight (kg)	Oxide	Oxide weight (kg)	Weight in glass (kg)
Low-level waste double-shell slurry feed simulant	88.84	Na_2O	18.81	20.42
		K_2O	1.43	1.64
		Al_2O_3	3.16	10.13
		Other	1.61	3.18
Bayer alumina	4.68	Al_2O_3	4.65	--
		Na_2O	0.01	--
Boric acid	9.08	B_2O_3	5.09	5.09
Southern bentonite	3.00	Al_2O_3	0.47	--
		CaO	0.13	5.09
		K_2O	0.02	--
		SiO_2	1.53	53.41
		Other	0.26	--
Diatomite	41.48	Al_2O_3	1.61	--
		CaO	0.27	--
		Fe_2O_3	0.84	1.04
		K_2O	0.14	--
		Na_2O	1.54	--
		SiO_2	35.67	--
		Other	0.77	--
Micro-Cell*	15.55	Al_2O_3	0.24	--
		CaO	4.69	--
		Fe_2O_3	0.20	--
		K_2O	0.04	--
		Na_2O	0.05	--
		SiO_2	7.66	--
		Other	0.55	--
Glass maker's sand	8.58	Al_2O_3	0.01	--
		SiO_2	8.55	--
Powdered sugar	2.80	--	--	--
Activated carbon	4.72	--	--	--
Total	178.73	--	100.00	100.00

*Micro-Cell is a trademark of Celite Corp.

Table 4-10. Batch Formulation, Type B Feed.

Batch material	Weight (kg)	Oxide	Oxide weight (kg)	Weight in glass (kg)
Low-level waste double-shell slurry feed simulant	88.84	Na_2O	18.81	20.47
		K_2O	1.43	1.58
		Al_2O_3	3.16	9.99
		Other	1.61	2.53
Bayer alumina	5.14	Al_2O_3	5.11	--
		Na_2O	0.02	--
Boric acid	8.90	B_2O_3	4.99	4.99
Limestone	8.58	CaO	4.70	4.99
		Other	0.10	--
Diatomite	44.13	Al_2O_3	1.71	--
		CaO	0.29	--
		Fe_2O_3	0.89	0.89
		K_2O	0.15	--
		Na_2O	1.64	--
		SiO_2	37.94	54.56
		Other	0.82	--
Glass maker's sand	16.69	Al_2O_3	0.01	--
		SiO_2	16.62	--
Powdered sugar	2.80	--	--	--
Activated carbon	4.72	--	--	--
Total	179.80	--	100.00	100.00

blender. A stiff plastic wet feed from the double ribbon blender was loaded onto an inclined rubber belt with overhead heat lamps, which partially dried the feed and delivered it to an inclosed steel belt dryer where the drying and feed reductant reactions were completed. This process produced prereacted Type B feed pellets with particle sizes ranging from ~0.32 to 5.1 cm.

4.5.2.3 Test Monitoring and Sampling. Critical parameters, such as temperatures, pressures, and current/voltage/power, were continuously monitored and recorded on a personal computer. Manual measurements, such as cold-cap height and electrode weights, were recorded in operations logbooks. The offgas from the melter was monitored and sampled by Entropy, Inc. in the

melter plenum, exit duct, and several other points throughout the air pollution control system. Glass temperature exiting the melter drain was continuously monitored with an optical pyrometer. Melt temperatures within the melter were not monitored.

Samples were taken of the Type A pellets before they were saturated with simulant, and after drying and reacting. Each batch of Type B feed was sampled as it came off the belt of the reaction furnace.

During the WHC1 test, glass product from the melter was sampled periodically and after certain portions of the test such as the power off idle and the hot idle. Samples of the material carried over to the thermal oxidizer, the cyclone separator, and baghouse were taken after the demonstration run was completed. Scrubber solution samples were taken periodically throughout the test. Offgas measurements were made by Entropy, Inc. Sampling of the offgas system products throughout the run was planned, but was not possible because the rotary air locks on the cyclone separator and the baghouse became clogged.

During the WHC2 and WHC3 test runs, glass samples were taken periodically, and offgas product samples were taken at the end of the runs. No offgas monitoring was performed by Entropy, Inc. during these runs. Additional details on test monitoring and the specific location of the sampling points are presented in the test plan (WHC-SD-WM-VI-021 [Eaton 1995e]).

4.5.2.4 Test Chronology. A summary of the test chronology for feed preparation and Phase 1 test runs WHC1, WHC2, and WHC3 is provided below.

January 15 - February 16, 1995--During this period, 1,784 kg of Type A feed and 11,889 kg of Type B prereacted dry melter feeds were produced. These melter feeds were stored in plastic-bag-lined 55-gal (208-L) steel drums.

March 8, 1995--The carbon electrode melter was started at 0455 on a mixture of powdered limestone, alumina, and rutile silica. This $CaO/Al_2O_3/TiO_2/SiO_2$ composition, following quenching and grinding, forms a fast-setting hydraulic cement and had been previously melted by the USBM for the Tree Hugger Corporation (TH). The use of this material (TH feed) for startup is significant because residues in this material appeared to remain in the melter throughout the WHC1 run. Feeding of TH feed was started and ~3 tonne of TH feed were used before changing to the Type B Hanford Site LLW feed. Difficulties were experienced in pouring the TH melt due to its melt viscosity and continuous tapping of the TH melt could not be achieved.

Feeding of Type B feed started at 1022 and initially resulted in a more fluid melt that was continuously tapped until 1408 when melter power was turned off to add electrode segments. Power was resumed at 1419, but the continuous drain flow could not be restarted. The first set of offgas samples and CEM measurements was taken at ~1600. Between 1645 and 1835, ~247 kg of lime and 45 kg of boric acid were added to the melter to lower the melt viscosity and allow starting of the drain. The drain was restarted at 1908 and flushing the melter melting Type B feed continued until 2240 when the power was shut off for 20 minutes to slip the electrodes.

The 'steady-state' portion of the WHC1 demonstration run started at 2330 on March 8, 1995, with a power input of 450 kW and a feed rate of 341 kg/h.

March 9, 1995--At 0328, the power was interrupted for 16 minutes to add electrode segments. At 0735, the power was turned off to demonstrate the ability to stop for a period of 1 hour and restart. The power was started twice momentarily during the hour power off period to verify that the melt was still sufficiently conductive for restart without addition of conductive feed. Melting was resumed at 0835. The glass pour stream temperature was ~1600 °C, whereas the 100 poise viscosity melt temperature of the LD6-5510 target glass formulation was 1296 °C. At 1057, the power and feed rates were cut back to 350 kW and 136 kg/h, respectively, in an attempt to melt and continuously pour at lower temperatures. The decrease in power seemed to slightly decrease the glass pour stream temperature, but it became difficult to maintain a continuous pour at the reduced power level.

Periodic offgas Method 5 samplings and CEM measurements continued throughout March 9. Feeding was stopped and extended hot idle of the melter demonstrated between 1515 and 1753. At 2000, the feed was switched to Type A. No significant operational differences between Type A and B feeds were detected.

March 10, 1995--The WHC1 demonstration run was completed at 0300. Attempts to drain the furnace through the hearth bottom center drain were unsuccessful even after adding lime to fluidize the melt. Power was turned off at 0330 and the furnace was allowed to cool without draining.

April 10, 1995--Following the WHC1 test, the water-cooled copper drain fixture was replaced by a graphite tube drain, the power transformer taps changed to operate the furnace at lower voltages, and adjustments were made to the offgas system. The USBM WHC2 run was started at 0735 on April 10 by initially heating the glass left in the melter hearth from the WHC1 run. Feeding Type B feed was started at 1130 at a feed rate of ~91 kg/h. Using the lower voltages, lower melting temperatures were achieved, but it was still difficult to maintain a continuous tap at these lower temperatures (1350 to 1500 °C). At 1435 on April 10, the offgas port became plugged, and although the plug was partially removed by using a steel rod through the analysis port, the plug soon re-formed and the offgas line remained plugged for the duration of the run. The dried, prereacted feed used in this test produces little offgas compared with the slurry feeds used in some other technologies, so it was possible to continue the test without the service of the offgas system allowing the melter to vent through the feed ports. The WHC2 run was terminated at 1724 without attempting to drain the melter.

May 3, 1995--Before starting the WHC3 run, 20.3-cm (8-in.) diameter sections were attached to the ends of the electrodes to decrease current density at the electrode-glass interface, and additional modifications were made to the drain. The USBM WHC3 run was started at 0735 on crushed product from a previous INEL run with carbon steel punchings lining the bottom of the hearth. The steel punchings were used to test the possibility of introducing oxygen into the bottom of the melter to oxidize precipitated metal in the melter. Gas flow to the hearth bottom was changed from Ar to O_2 to demonstrate oxidation of the Fe and dissolution in the melt. Additional

carbon steel punchings (91 kg) were added at 1102. The O_2 injection lance failed by burning off at 1409 and the oxygen injection test was terminated.

At 1637, the melter was drained through the bottom hearth drain and feeding of Type B feed started at 1646. At 1833, the melt level reached the side drain tap hole level, but would not drain through the 1.27-m (0.5-in.) graphite tube insert. The graphite insert was removed and continuous tapping of the glass at 1400 °C was initiated at 1842. At 1905, the power was increased from 325 to 375 kW in an attempt to increase the feed rate and maintain a more continuous pour. By 2017, only intermittent glass pouring was possible. Lime was added at 2122 (38 kg) and at 2148 (55 kg) to fluidize the melt, and continuous pouring at a glass pour stream temperature of ~1500 °C was initiated. At 2210, power was again reduced to 250 kW.

May 4, 1995--Melting of all remaining Type A and B feeds was completed at 0130. The melt temperature measured at the exit from the melter ranged from 1400 and 1500 °C with an average feed rate of 723 kg/h and ~250 kW of power. The melter was drained through the hearth bottom drain at 0145 with optical temperature measured on the final bottom drain pour stream ranging from 1490 to 1445 °C.

A more detailed chronology of the WHC1, WHC2, and WHC3 runs, as well as details on power, feed rate, and temperature for the three tests, is provided in the USBM Phase 1 test report (WHC-SD-WM-VI-030 [Eaton 1995f]).

4.5.3 Results and Observations

As is to be expected when attempting new processes or new compositions, the feed preparation and the first melting test (USBM WHC1) were learning experiences and did not proceed particularly smoothly. Significant results and observations follow.

4.5.3.1 Feed Processing. Following laboratory development experience, and initial lessons learned during pilot-scale mixing, drying, and reacting, production of feed for the melter runs proceeded well. A total of 1,784 kg of Type A feed and 11,889 kg of Type B feed were produced having bulk densities of 0.43 and 0.53 g/cm^3, respectively. The feed that was produced was dry and not hygroscopic during the several months of storage between production and melting. The sugar plus activated carbon feed reductant additives effectively destroyed 78% of the feed NO_3^-/NO_2^- on the average during Type B feed preparation. However, the degree of reaction between the carbon reductant and NO_3^-/NO_2^- varied between >90% down to ~15% for feed particles from various Type B feed batches. Some of the variability between batches of Type B feed can be attributed to the difference between processing at day and at night. With warmer ambient temperatures during the day, the simulant and consequently the mixture of simulant and dry minerals were less viscous than at night when the simulant became thick. The degree of reaction for Type A feed was not determined.

4.5.3.2 Melt Rates. The highest steady processing rates were achieved during the WHC1 and WHC3 runs. During the first 7.5 hours of the WHC1 run, a processing rate of ~270 kg/m^2/h glass was achieved, but the average glass processing rate during the 24-hour period, not counting the 3 hours of planned

downtime, was ~250 kg/m^2/h. Average glass melting rate in the WHC2 run was 142 kg/m^2/h. Increasing electrode diameter for run WHC3 resulted in higher glass melting rates that ranged from ~170 to 365 kg/m^2/h, with average glass melting rate estimated at ~270 kg/m^2/h.

4.5.3.3 Volatility and Entrainment Losses. In general, there was relatively high volatility of B, alkali metals, and halides in the USBM test runs. The volatility losses were partially the result of excessively high melting temperatures required as a result of a drain configuration that was ineffective for continuous pouring of viscous glass. Alkali metal and B losses were reduced for runs WHC2 and WHC3 as a result of modifications to the melter and procedures that reduced maximum melt temperatures.

The main objective of run WHC2 was to reduce maximum temperatures near the electrodes by lowering the electrode voltage, and hopefully reduce volatility and entrainment losses. An approximate 50% reduction in B loss was achieved in run WHC2. As expected with the lower power levels, the processing rate was also lower. The average glass production rate was reduced from ~250 kg/m^2/h in run WHC1 to ~142 kg/m^2/h in run WHC2.

Larger diameter electrodes were used in the WHC3 run to reduce the current density at the electrode/melt interface as a further attempt to reduce maximum melt temperatures near the electrodes and reduce volatility and entrainment losses. One effect of the larger electrodes was to achieve higher melt rates while gaining further decreases in volatility losses. The WHC3 peak melt rate of ~365 kg/m^2/h estimated for periods of ~1 h, and the WHC3 average melt rate of ~270 kg/m^2/h, exceeded melt rates estimated for run WHC1. Additional details regarding the volatility and entrainment losses from all three USBM runs are presented in Section 6.0.

4.5.3.4 Electrode Consumption. During run WHC1, average electrode consumption was 12.6 kg/tonne normalized to the quantity of glass produced. The USBM did not report electrode consumption for run WHC2, but did report a value of 25 kg/tonne for a period that included an INEL run, the WHC2 run, and overnight hot idling of the melter. Carbon loss from the 20.3-cm (8-in.) diameter electrode stubs in run WHC3 was 5.4 kg/tonne based on glass and metal products. Total electrode consumption from the 10.2-cm (4-in.) diameter electrodes and the 20.3-cm (8-in.) diameter stubs was 10.5 kg/tonne. Considering that O_2 gas was bubbled through the melt for a portion of the WHC3 run, increasing electrode diameter appears to result in reduced electrode consumption.

4.5.3.5 Product Glass. Some of the glass from the WHC1 run was characterized for composition, redox state, uniformity, and durability. These data are discussed in Section 5.0. Physical characterization revealed cords and inclusions in the glass product. Examination of the cord composition indicated that the cords likely originated from the TH startup material, residues of which remained in the melter throughout run WHC1 and did not uniformly mix with the melt. The inclusions were shown to be Mo metal, apparently reduced from the original MoO in the DSSF simulant. Except for the inclusions previously mentioned, the product appeared to be glassy and well reacted. The Fe^{+2}/Fe ratio for the glass was essentially 1.0, indicating the glass was very reduced.

4.5.3.6 Refractory Wear. Refractory corrosion was evident by visual examination of the melter, and by the increase in Cr content in the product glass. Wear of the upper wall refractory lining during the WHC1 run was due in part to upset conditions during startup. When the operators had difficulty maintaining a continuous tap, the level of melt in the melter rose to above the intended glass contact refractory level. After corroding a significant amount of refractory, however, wear did not proceed to the melter wall, but formed a frozen glass skull layer as was intended and did not wear further.

4.6 WSTC

The WSTC, a division of Westinghouse, performed Phase 1 testing at the Westinghouse Plasma Center, located at the Westinghouse Waltz Mill Site in Madison, Pennsylvania. The WSTC Phase 1 testing was performed under WHC contract MMI-SVV-384212.

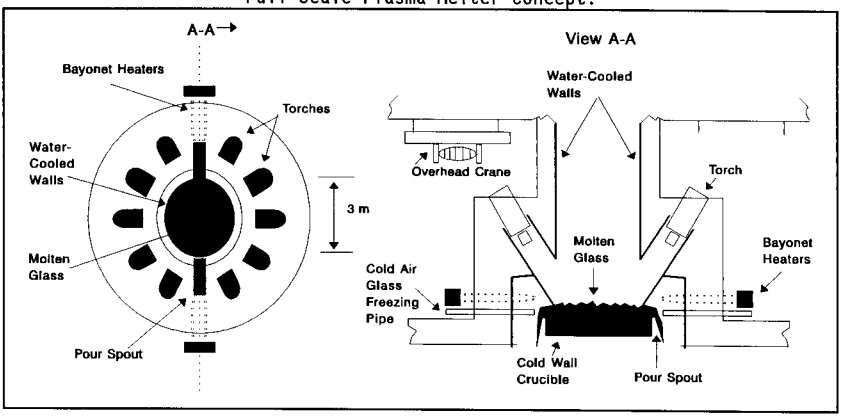
4.6.1 Melter Technology Description

The Westinghouse plasma torch is the heat source for the melter system proposed by WSTC for Hanford Site LLW vitrification. Hot gases from a plasma plum are directed down a tuyere from the plasma torch to a melt crucible. A slurry feed of liquid LLW, in addition to glass-former additives, is injected into the tuyere where the feed is rapidly heated and carried along with the hot gas plume from the plasma torch to the melt crucible. Pre-melted powdered frit was used as the sole glass-former additive for Phase 1 testing. The slurry feed could also be prepared using batched raw glass-former materials. No reductant additives are used. Glass was poured from the melt crucible via a simple overflow drain. The tuyere, and likely other high wear glass contact components, will be water-cooled and rely on the formation of a frozen glass skull layer for protection and extended life.

4.6.1.1 Full-Scale Concept. The WSTC has proposed the use of three or four melters (67 or 50 tonne/day each) to achieve the 1994 baseline glass processing capacity of 200 tonne/day for the LLW vitrification facility. The WSTC has provided its conceptual plan for a full-scale plasma melter for LLW in a technical information report (WHC-SD-WM-VI-015 [Hendrickson 1995a]). As shown in Figure 4-8, each full-scale melter is ~3 m internal diameter and is fired by ten plasma torches mounted on individual tuyeres configured around the melter circumference. The tuyeres are mounted at an angle of ~30° off vertical. Each tuyere, as a separable unit, would require cooling water for its jacket and a waste feed line. The plasma torch requires deionized water for electrode coolant and filtered working gas. Each torch would be expected to operate at ~2.0-MW power.

The plasma torches would be removable for electrode replacement and periodic maintenance while the melter continues operation. An isolation valve to close the tuyere opening when the torch is removed may be required, particularly if a replacement torch is not immediately installed.

Figure 4-8. Westinghouse Science and Technology Center Full-Scale Plasma Melter Concept.



Scaleup is not considered to be difficult for the plasma vitrification process. The full-scale melter is scaled up from the pilot-scale system used for Phase 1 testing by adding additional torches. The primary issues of scale are those of feed batch-former mixing and preparation, the technical difficulties of handling a number of separate feed streams to individual tuyeres, and the number of connections and jumpers required for multiple tuyeres.

4.6.1.2 Technical Issues. The WSTC Phase 1 testing has indicated the following technical issues.

Volatility and Entrainment Losses--Feed component entrainment losses were the second highest observed during Phase 1 testing. Volatility losses were also high, comparable to those observed in the USBM WHC1 and WHC2 test runs. It is estimated that 22% of the boria was volatilized from the pre-melted frit which was the sole source of the boria in the melter feed. The WSTC plasma melter cannot be operated in a 'cold-top' mode with cold batch coverage to suppress volatility as can Joule-heated melters and possibly the carbon electrode USBM melter.

Frit Versus Batched Glass Formers--Pre-melted powdered frit was used as the sole glass-former additive during Phase 1 testing. Because most of the alkali (primarily Na) is supplied from the LLW, the required low alkali content frit is very refractory and difficult to manufacture. As a result, using frit as the glass-former material for LLW vitrification is expected to be significantly more expensive than using batched separate glass-former materials. If separate glass formers are used, it has not yet been demonstrated that they will react completely forming a microscopically uniform glass phase with the rapid heating and relatively short residence time at

temperature in the WSTC melter. Also, it is expected that boria fed as boric acid with batched glass formers would be much more volatile than boria fed as a pre-melted frit component.

Refractory Erosion--Significant erosion of corundum-mullite cast refractory used to line the tuyere was observed during Phase 1 testing. Part of the problem was likely a 17° bend built into the tuyere to provide clearance between the plasma torch and an overhead I-beam when the tuyere length was extended for Phase 1 LLW vitrification testing. Less wear of the tuyere refractory should occur with a straight tuyere. However, the tuyere can be expected to be a high wear area. A cold wall tuyere lined with a frozen glass skull is an option for reducing wear and extending expected life for the tuyere and other high wear glass contact areas.

Maintenance and Operability--The Westinghouse plasma torch requires periodic maintenance to replace electrodes and components within the torch (Hendrickson 1995a [WHC-SD-WM-VI-015]). Estimated life for the downstream electrode is 500 to 1,000 hours. Upstream electrode life is estimated to be 1,000 to 1,500 hours and the plasma torch field coil life is estimated at 5,000 hours. Each torch requires connections for electrical power, cooling water, and process gases. Connectors and remote torch handling equipment will likely need to be developed to allow for removal of individual torches and transport to a contact maintenance facility for periodic maintenance and for re-installation of repaired torches. With ten torches per melter, it is highly desirable that removal and re-installation of individual torches be accomplished without shutting down the melter and interrupting production. Costs associated with the maintenance requirements for the plasma melter need to be evaluated; however, cost estimates at this time would be purely speculative without specific design concepts.

Feed Mixing and Composition Control--The current WSTC feed concept is to continuously mix glass-former additives (frit in Phase 1) with liquid LLW in a progressive cavity slurry pump and directly inject the resulting slurry into the melter tuyeres. Assurance that the LLW and glass-former feed streams are accurately metered will be required to ensure product composition control. It appears that accurate control of the frit feed rate was not achieved during Phase 1 testing. One solution to this potential process control issue would be to operate with pre-batched slurry feed that is characterized before being advanced from the slurry mixing tank to the melter feed tank. However, additional tankage and radioactive feed handling operations are required for pre-batched slurry feeding.

4.6.1.3 Technology Strengths. The following strengths are identified for the WSTC plasma melter concept.

- Flexibility--This melter can melt feeds with a variety of compositions and characteristics. The melter can be shut down and restarted with relative ease and is not sensitive to glass melt properties such as electrical conductivity.

- Compact size--Based on a melt pool of ~1 m diameter, and a melting rate of ~300 kg/h demonstrated in Phase 1 testing, the specific melt rate was several times greater than demonstrated with slurry-fed Joule-heated technologies.

- The Westinghouse plasma torch is a developed technology with an established performance record in industrial applications. Safety issues associated with using the plasma torch as a heat source in a radioactive process are expected to be less of a problem than with using fossil fuel combustion. Offgas volumes requiring treatment are also less with plasma heating than with combustion heating.

4.6.2 Phase 1 Testing

Phase 1 testing was executed as a series of three scoping tests and a final '24-hour' demonstration test. These tests were of 4, 8, 10, and 26 hour duration, respectively. The tests produced ~1.26, 2.38, 2.77, and 7.37 tonne of glass product with applied power of 1.65, 1.53, 1.55, and 1.55 MW, respectively. The test dates were October 13, November 3, November 17, and December 7-8, 1994. Testing was conducted in accordance with an approved test plan (WHC-SD-WM-VI-011 [Hendrickson 1994]), and test results were reported by WSTC in a final Phase 1 test report (WHC-SD-WM-VI-016 [Hendrickson 1995b]).

4.6.2.1 Test Facilities. The WSTC Waltz Mill Plasma Center contains the pilot-scale plasma-fired cupola furnace where Phase 1 LLW vitrification testing and a prior Hanford Site tank waste calcination demonstration were conducted (Delegard et al. 1994). A schematic diagram of the overall plasma melter system as configured for the Phase 1 LLW melter testing is shown in Figure 4-9. The plasma melter is 6.7 m in height, with a furnace shaft outer shell diameter of 1.2 m and an internal diameter of 0.76 m. The melter is fired by a single Westinghouse Marc-11 plasma torch mounted on a tuyere that directs the hot plasma plume toward the melt crucible at the bottom of the melter. A baffle plate suspended in the shaft reduces radiative heat losses up the shaft. The melt crucible is mounted to the bottom of the shaft and is removable from the cupola furnace shaft. A tap hole on the bottom side of the crucible connects to an overflow side pour spout for glass product removal. The cupola shaft is lined with an Al_2O_3/SiO_2 refractory, the crucible is lined with a Cr_2O_3/Al_2O_3 'ruby' refractory, and the tuyere is lined with pre-formed Al_2O_3/CaO refractory insert sleeves. A schematic diagram showing the lower melter shaft, crucible, tuyere, and pour spout is shown in Figure 4-10. The tuyere was extended for the Phase 1 testing and the extension section (not shown in Figure 4-10) contained a 17° bend to provide clearance from an overhead beam.

In the melter feed system developed by WSTC for Phase 1 testing (Figure 4-9), the liquid LLW simulant is continuously mixed with glass formers (frit) in a progressive cavity slurry pump and directly injected as a slurry into the plasma plume within the tuyere where it undergoes rapid evaporation, calcination, and initial melting. The gas/solid stream exits the tuyere and the entrained solids impinge upon the glass pool in the crucible and become dissolved in the melt. Offgas proceeds up the melter shaft while the glass product is continuously tapped from the overflow pour spout and poured into carbon steel mold boxes.

The gas volumes required to operate the plasma torch are much smaller than those required for conventional combustion heating. The offgas travels up the shaft, is partially air quenched by air inflow from the charge door, flows out the top of the melter shaft via a horizontal duct to a vertical duct

Figure 4-9. Westinghouse Science and Technology Center Plasma Center Pilot-Scale Melter System as Configured for Phase 1 Low-Level Waste Melter Testing.

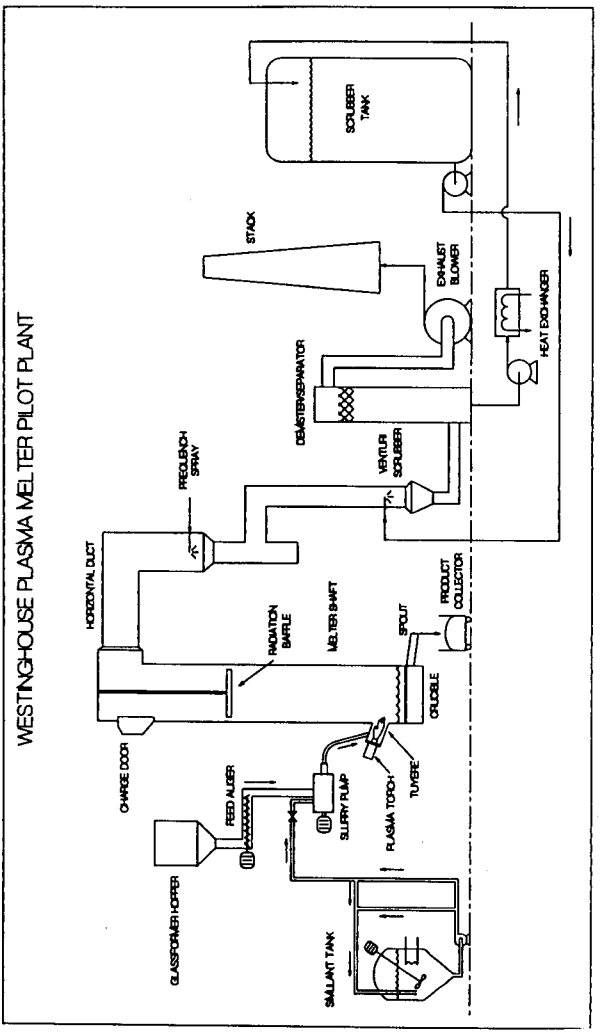
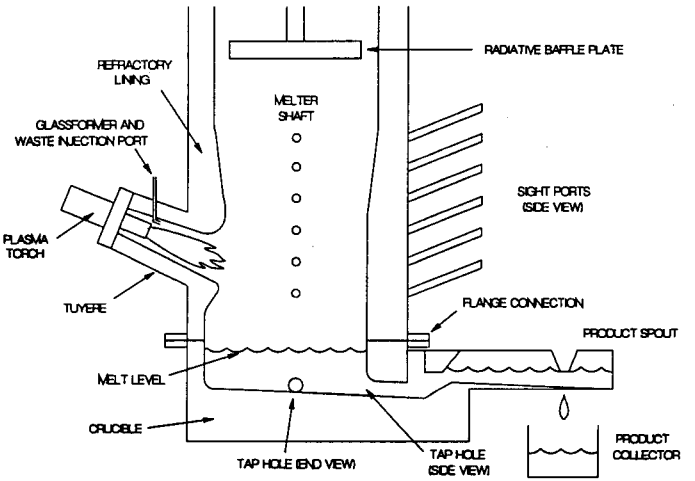


Figure 4-10. Schematic Drawing of Westinghouse Science and Technology Center Pilot-Scale Plasma Melter Tuyere, Crucible, and Pour Spout.



where it is water quenched, and is scrubbed in a venturi scrubber. The treated offgas passes through a demister and is sent out the stack through an exhaust fan. The separated scrubber liquor is cooled by passage through a 1-MW heat exchanger and recycled to the 15-m^3 capacity scrubber tank.

Additional heating and shrouding are required in the pour spout region to sustain sufficiently low glass viscosity to maintain continuous pouring. The tuyere and crucible are water-cooled by copper tube cooling coils. The melter shaft is cooled with an external film of falling water.

4.6.2.2 Feed Preparation and Glass Formulation. The WSTC Phase 1 glass formulation was developed with the support of the SRTC. The use of a pre-manufactured frit was chosen as the sole glass-former additive to simplify feed batching because the WSTC did not have equipment to batch and blend the required pilot-scale quantities of glass formers from raw materials. The use of pre-melted frit would also facilitate melting reactions and product homogenization with the relatively short residence time at temperature in the plasma melter, and would also reduce boria volatility. The Phase 1 target glass and frit formulations are given in Table 4-11. Lithia was added as a flux to lower the frit melting temperature.

For purposes of rapid procurement, Cataphote in Jackson, Mississippi, was selected to provide the first batches of frit used in the initial scoping test runs. Ferro Corporation of Cleveland, Ohio, provided the remainder of the frit, including all the frit used for demonstration test Run #4. The particle size of the frit provided by Ferro was much finer (90% <50 μm, 10% <3 μm) than the Cataphote frit. The fine particle size of the Ferro frit, while

Table 4-11. Phase 1 Glass Formulation.

Vitrified species	Frit composition (%)	Glass product composition (%)
SiO_2	57.20	42.90
Al_2O_3	19.44	17.77
Na_2O	--	18.12
B_2O_3	12.60	9.45
CaO	6.20	4.65
ZrO_2	2.80	2.10
K_2O	--	1.44
Li_2O	1.10	0.83
Fe_2O_3	0.66	0.50
SO_3	--	0.21
P_2O_5	--	0.19
Cs_2O	--	0.15
MoO_3	--	0.15
SrO	--	0.11
Cr_2O_3	--	0.04
MgO	--	0.002
MnO_2	--	0.002
NaF	--	0.64
NaCl	--	0.59
NaI	--	0.16

contributing to rapid reaction kinetics with the LLW simulant, also likely contributed to enhanced offgas particle entrainment losses. Additionally, the Ferro frit was contaminated with ~2% BaO due to its production in a melter previously used to melt a baria containing glass.

After the glass frit was loaded from drums into a glass-former hopper, it was volumetrically metered through an auger. The rotation speed of the auger at the base of the hopper was calibrated to provide the desired volumetric frit feeding rate. The LLW simulant was metered off a continuous recirculation loop from a warmed and agitated* simulant feed tank through a mass flow meter. For the Phase 1 demonstration test, the liquid LLW simulant

*The simulant feed tank agitator was not operational for the Phase 1 demonstration test.

and frit feed rates were initially calibrated to achieve a theoretical waste loading of 28% to compensate for a 15% Na_2O volatility loss that was expected based on the previous scoping test results. The frit and liquid LLW simulant feed streams were fed to a small feed hopper that fed a progressing cavity (Moyno*) slurry pump. At the bottom of the small hopper, a rotating paddle/auger initially mixed the liquid LLW and frit and fed the mixture to the slurry pump, which pumped the slurry into the tuyere through a 0.95 cm diameter stainless steel pipe.

4.6.2.3 Test Monitoring and Sampling. The tests were monitored with continuous online instrumentation and by direct liquid and solid sampling techniques. Sample points for the test operations included the following:

- Glass frit from the frit feed tube
- LLW simulant settled solids
- LLW simulant from the injection line to the slurry pump
- LLW simulant/glass frit slurry from the feed injection line to the tuyere
- Product glass from the glass pour spout
- Glass temperatures within the crucible and at the pour spout
- Shaft gas NO_x, H_2, CO, CO_2, and O_2
- Method 5 offgas aerosol/particulate samples from the offgas duct
- Scrubber solution from the recirculation line
- Scrubber sump liquids/solids
- Offgas duct deposits.

4.6.2.4 Test Chronology. Three scoping test runs and a '24-hour' demonstration test run were conducted in the pilot-scale plasma melter. The three scoping tests are discussed in Appendixes A through C of the WSTC Phase 1 test report, and demonstration test Run #4 is discussed in the main body of this same test report (WHC-SD-WM-VI-016 [Hendrickson 1995b]).

October 13, 1994--The first scoping test was run on October 13. The melter was partially preheated by burning 300 kg of foundry coke charged to the cupola furnace shaft. Demonstration of LLW glass melting under a bed of coke to reduce volatility and entrainment losses had been an objective of the first scoping test, but was abandoned. Approximately 1,260 kg of glass were melted in ~4 hours using the LLW simulant and Cataphote frit. Problems were experienced in maintaining thermal stability within the melter and pour spout during this first scoping test.

*Moyno is a trademark of Robbins and Meyers, Inc.

November 3, 1994--The second scoping test was run on November 3. A radiation baffle suspended in the melter shaft reduced heat loss and thermal instability within the melter. Approximately 2,377 kg of glass were melted in ~8 hours using the LLW simulant and Cataphote frit Lot 2. The radiation baffle successfully controlled the temperature and the melter thermal stability. However, damage to the radiation baffle indicated a need for design modifications. Shrouding and auxiliary heating of the pour spout with a gas torch improved glass pouring. A 1-kg $Ba(OH)_2$ spike was added to the feed at 1625 to determine melter residence time. Barium was detected in glass samples from the pour spout a few minutes after injection into the tuyere, and most of the Ba was flushed from the melter after 1 hour.

November 17, 1994--The third scoping test was run on November 17, and produced 2,770 kg of glass over 10.5 hours. Cataphote Lot 2 frit was used during the first 2 hours and Ferro Lot 1 frit was used for the remainder of this scoping test. The modified radiation baffle performed well.

December 6, 1994--Pretest preparations performed for the '24-hour' demonstration test included detailed torch electrode measurements to evaluate wear, feed system calibrations, gas sampling system calibrations, crucible refractory firing, and completion of LLW simulant transfer to a new larger simulant feed tank. Previously completed following scoping Run #3 were profiling of shaft and crucible refractory and replacement of the tuyere refractory. The scrubber solution tank had been cleaned and filled with 13,250 L of city water. The slurry feed system was reconfigured with a larger hopper for collection of the liquid LLW and frit feed streams and a new Moyno progressive cavity slurry pump. Following seal placement, the crucible section was mounted to the melter shaft and the system was fired overnight with gas-fired torches to preheat the refractory.

December 7, 1994--The plasma torch was started at 0907 at 810 kW. Torch power was incrementally increased to ~1500 kW. The '24-hour' demonstration test formally began with waste feed initiated at 1255. Glass product began flowing from the pour spout at 1330 at 1370 °C. Some fuming was seen from the glass stream with the conjecture that it was sodium borate. The first of two glass pull rate samples was taken at 1557, indicating a pull rate of 280 kg/h. Based on simulant and frit feed rates, the theoretical steady-state pull rate was calculated to be 365 kg/h, suggesting process losses of 23.2%. Test sampling and monitoring proceeded smoothly throughout the test, but were, in general, highlighted by high indicated process losses. Steady-state operation of the melter and glass pouring proceeded through the evening with no evidence of operational difficulties.

December 8, 1994--A small increase in melter back pressure and restricted offgas flow was noted as early as 0533. By ~1100, fuming and emissions from the cupola charging door near the top of the melter shaft began to cloud the upper elevations of the high-bay pilot-plant facility. It was believed that this was being caused by solids deposition and buildup in the offgas train downstream from the melter. Operations staff found that a high-pressure differential was occurring in the venturi scrubber area. At ~1225, operators and the facility engineering manager tapped ducting causing some material to break free (audibly) and enter the bottom of the demister-separator. It appears that some of this material became entrained in the scrubber solution and partially blinded the scrubber solution heat exchanger causing the liquid

level in the separator to rise and the offgas blower to overamp. The blower overamperage caused the safety system interlocks to shut down the torch and feed system at 1257. Within 25 minutes, the crew had cleared the separator and had the torch and feed back online. The torch was reignited at 1324 and feed restarted at 1338. Glass was flowing again within 15 minutes of feed restart. Because of the blinding, the heat exchanger was taken offline. The loss of heat removal from the scrubber solution would limit the remaining test length as the scrubber solution approached maximum acceptable temperatures.

Glass melting operations continued until 1515 when the feed system was stopped and oxygen lances were employed to open the crucible bottom drain. The plasma torch was shut off at 1530 with a total elapsed torch operating time of 30.3 hours. Elapsed melter feeding time was 25.7 hours and total glass produced was ~7.4 tonne.

The torch was removed at 1830 and the tuyere opened. Some material accumulations existed within the tuyere in the area of the removed torch. Overall tuyere wear was less than anticipated, and a glass skull had formed in the area of greatest refractory wear within the tuyere. Continued system ventilation to cool the refractory yielded material fragments cascading audibly through the lower horizontal segment of the offgas train toward the venturi scrubber.

December 9, 1994--The crucible was removed during the morning and photographs were taken of the lower melter shaft refractory and material remaining in the crucible. The crucible refractory had little wear. The radiation baffle in the shaft was in good condition.

The sump leg on the offgas leg was drained, yielding ~100 L of liquid and sludge. Because the leg had not been drained during the last several years of operation, the materials in the leg were anticipated to be of various sources. Samples were acquired for analysis. During the late afternoon, the shaft refractory had been sufficiently cooled to allow visual observation of the upper shaft and upper horizontal section of the offgas ducting. No significant buildup occurred in the shaft. However, 66 kg of solidified deposited material were recovered from the horizontal offgas duct from the top of the melter shaft.

4.6.3 Results and Observations

Results and observations discussed in this section are primarily associated with demonstration test Run #4, conducted on December 7-8, 1994. This test, which ran for ~26 hours under near steady-state conditions, produced 7,372 kg of glass.

4.6.3.1 Feed Processing. Analyses of four slurry feed samples taken from the melter feed line between the slurry pump and the tuyere indicated that the ratio of components derived from the simulant increased with time relative to components derived from the frit. Material balances around the slurry feed pump suggest a linearly declining rate of frit delivery, but this conclusion is not confirmed by the product glass composition data or a material balance on the quantity of frit fed through the frit hopper. Two concerns during feed

processing that may have affected the ability to control feed composition were: (1) the ability to meter and feed a uniform simulant composition, and (2) the lack of control over the frit delivery rate.

The high solids content of Optima Lot 2 simulant used for demonstration test Run #4 raised concern regarding the consistency of the simulant component feed rates. Acceptance characterization of the Optima Lot 2 simulant indicated 10.5*M* Na concentration with 47% settled solids content and 22% centrifuged solids content at 25 °C. All the LLW simulant to be used for demonstration test Run #4 was staged in a new large outdoor feed tank before the test. The outdoor temperature during the pre-test and testing period ranged from 0 to 10 °C. Transferring the settled sludge from the 208-L (55-gal) drums to the feed tank was difficult because of the high solids content that had settled as a thick sludge in the drums. Although an immersion heater in the feed tank held the LLW simulant at 40 °C, and the simulant was continuously circulated through an external loop to provide limited mixing, a tank agitator was inoperable during the test and not all the solids were redissolved or resuspended.

A second concern appeared to be control of the frit feed rate. This rate was metered by an auger at the bottom of the frit hopper which ran at a constant pre-calibrated rotation speed. It was concluded that the changing slurry feed composition was most likely caused by inadequate control of the frit feed rate. However, the frit feed materials balance data are not unambiguous and this conclusion was based primarily on data indicating that control of the LLW simulant feed rate and simulant uniformity were not the problem. Simulant delivery to the slurry pump was metered through a mass flow meter which recorded instantaneous and cumulative flow. The target simulant feed rate was 3.875 L/min and the average half-hourly measured simulant feed rate was 3.767±0.080 L/min. Analyses of simulant samples taken from the recirculation loop and the feed line to the slurry pump were relatively uniform and did not show increasing component concentrations with time. Average measured Na concentration was ~10.5*M* and the simulant samples contained ~30% settled solids and ~12% centrifuged solids when later characterized.

The uncertainties in feed composition control experienced by WSTC highlight an important control issue with feed systems such as those used by PEI and WSTC where the feed is continuously mixed and directly fed to the melter. Although this type of feed system reduces the amount of radioactive feed processing required, accurate metering of the LLW and glass-former feed streams and control of the feed rate for one or both feed streams are required to achieve composition control with such feed systems. Equipment modifications to allow mass delivery rate metering of the frit or glass formers, and capability for continuous adjustment of the feed rates for the LLW and/or glass-former feed streams, are recommended minimum upgrades to ensure composition control for the WSTC feed system.

4.6.3.2 Melt Rates. Glass production rate with the single Marc-11 plasma torch operating at an average input electrical power of 1550 kW was ~300 kg/h. The energy requirement of ~5 MW·h/tonne demonstrated in the WSTC Phase 1 test is significantly greater than the ~1 MW·h/tonne achievable with cold-top Joule-heated melters. The crucible melt surface area was not provided, but is

estimated to be on the order of ~1 m^2, providing the highest melt area normalized steady-state melting rate (~300 $kg/h/m^2$) demonstrated for any vitrification during Phase 1 testing.

4.6.3.3 Volatility and Entrainment Losses. Based on analyses of four melter feed samples and simultaneous glass samples, gross entrainment loss was estimated to be 2.7%, and Na_2O and B_2O_3 volatility losses were estimated to be 15% and 22%, respectively (see Section 6.0). The estimated 22% B_2O_3 volatility loss is especially high considering that the pre-melted glass frit was the only B_2O_3 source. Only the B&W and USBM WHC1 tests exhibited greater B_2O_3 losses (the USBM WHC2 test B_2O_3 loss estimated at 23% was not significantly different from WSTC), and these tests used boric acid as a boria source.

The theoretical glass production for demonstration test Run #4 based on integrated feed data was 8,378 kg, whereas the actual glass production was 7,372 kg, indicating overall volatility and entrainment losses of 12%. Subtracting the estimated 2.7% entrainment loss, this would imply ~9.3% of this 12% loss was due to volatility. However, as previously discussed, there is considerable uncertainty in the feed materials balance data and loss estimates based on these data.

4.6.3.4 Product Glass. Even with the uncertainties in feed composition control and the relatively high volatile component selective losses experienced during the WSTC test, analyzed product glass compositions were relatively close to the target glass composition. The glass was well reacted, transparent, and green. The glass contained numerous cords, which is likely a result of short-term variations in feed composition coupled with a relatively low melt crucible volume (~130 L, ~1 h/turnover) in which only limited convection and mixing occurred. However, the compositional inhomogeneity associated with the cording was not sufficient to have a significant adverse effect on measured PCT durability results.

4.6.3.5 Offgas Deposits. The upper horizontal duct (30 cm diameter) was filled to a depth of 7 to 10 cm with a solidified deposit material. The mass of the deposited material recovered from the horizonal duct was 66 kg. Results from an analysis by CELS on a sample of this material are provided in Table 4-12. A more detailed estimate of the deposit composition by analyte and salt components based on additional analyses (accounting for 96.39% of deposit material total mass) is provided in Table 7-7 of the WSTC Phase 1 test report (WHC-SD-WM-VI-016 [Hendrickson 1995b]). The material appears to be primarily volatilized $NaBO_2$, $NaNO_x$, and NaOH in addition to lesser amounts of other volatile species and alumina and silica carried over as entrained frit particles.

4.6.3.6 Process Upsets. A process upset shut down the melter after ~24 hours of feed operation because dislodged deposited solids in the offgas system blocked the offgas scrubber solution flow. Waste feeding and melter operation were interrupted for 41 minutes while the blockage was cleared. The melter and feed were restarted and processing continued for another 2 hours before a controlled shutdown was carried out to terminate the test.

Table 4-12. Analysis of Deposit Samples from Plasma Melter Horizonal Offgas Duct.

Component[a]	Wt%[b]	Component[a]	Wt%[b]
Al_2O_3	8.16	Li_2O	0.60
B_2O_3	16.9	Na_2O	41.2
CaO	0.81	P_2O_5	0.23
Cr_2O_3	0.21	SiO_2	4.92
Cs_2O	0.35	SrO	0.17
Fe_2O_3	0.58	F	0.21
K_2O	4.16	Total	78.5

[a]Results were reported for analyzed elements on an equivalent oxide weight percent basis as if the sample were a glass. Actual phases present were likely primarily salts.

[b]Oxide basis weight percent of total sample weight.

4.6.3.7 Refractory Wear. The melt crucible, pour spout, and radiation baffle plate surface were lined with Harbison-Walker ruby plastic refractory material (75% Al_2O_3, 19% Cr_2O_3, 2% SiO_2, and 4% P_2O_5). There was little wear on the ruby refractory in these areas.

The vertical shaft of the melter was lined with Premier Refractories and Chemicals 90-RAM-PC refractory (91% Al_2O_3, 5% SiO_2, and 3% P_2O_5). This refractory showed some attack by the glass in the lower levels of the shaft where glass contact occurred with upward drilling of the refractory near the melt line. Some spallation of the refractory was also observed in upper regions of the shaft. It should be noted that the shaft refractory was ~5 years old and had been exposed to a wide range of aggressive chemical and thermal environments before the Phase 1 LLW melter tests were conducted.

The tuyere was relined with pre-formed sleeves of alumina-calcia aluminate refractory before demonstration test Run #4. As in the shorter scoping Run #3, the tuyere refractory showed significant wear during the first 4 to 8 hours of melter operation. The wear then slowed, apparently because of the formation of a protective frozen glass skull layer. The greatest wear was observed along the roof of the tuyere just downstream from the 17° 'dog leg' angle in the tuyere.

4.7 B&W

The B&W cyclone vitrification technology is based on 50 years of experience with slagging combustion units for the electric utility industry. Slag is typically produced as a vitreous by-product material from coal combustion as a result of mineral impurities in the coal. Babcock & Wilcox has modified an existing pilot facility cyclone combustor to demonstrate

vitrification of a variety of inorganic hazardous wastes. The B&W cyclone vitrification technology has been demonstrated in a soil vitrification application for the EPA as part of its Superfund Innovative Technologies Evaluation Program.

4.7.1 Melter Technology Description

The cyclone furnace is a water-cooled, horizontal cylinder attached to the wall of the main furnace cavity. The cyclone wall consists of a network of water-cooled metal tubes fitted with metal studs pointing into the center of the cylinder. A thin layer of refractory cement (19 to 51 mm) is imbedded between and over these studs to protect the metal structure. When operating, a layer of cold glass (skull) forms on the walls of the cyclone furnace and inhibits corrosion and erosion of the furnace. With time, the refractory cement that lines the cyclone furnace is replaced by a frozen glass skull. For waste vitrification applications, heat is supplied by the combustion of either natural gas or fuel oil. Although the flue gas temperature can reach 1500 °C, the glass temperature is ~1300 to 1350 °C.

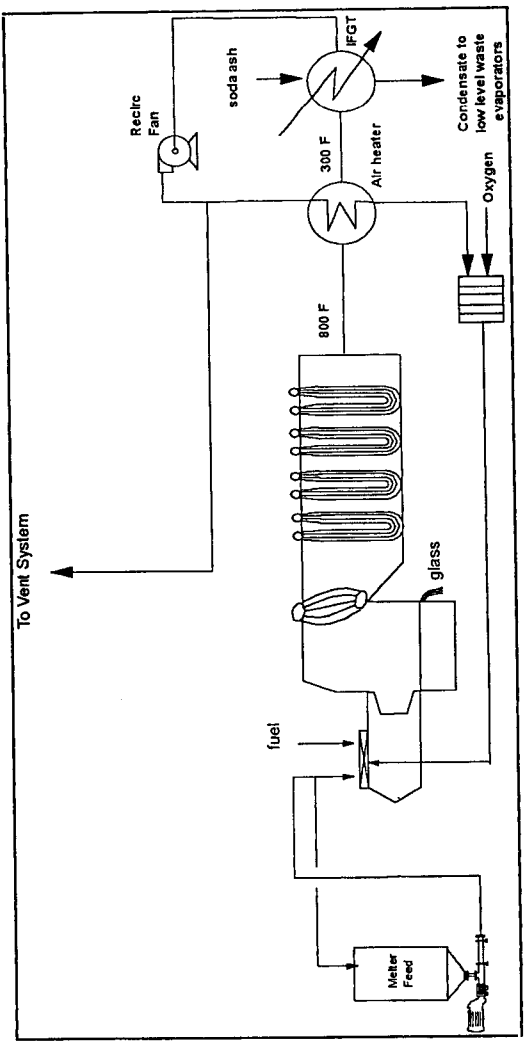
The B&W melter is fed a slurried material. The liquid wastes and dry glass formers are pre-mixed outside the melter and injected into the melter through an atomizing injection nozzle. Feed rheology is controlled by the size distribution of the glass-former additives. The slurry feed is injected onto the cyclone wall where it melts and flows down the cylindrical walls and is collected in the bottom of the cyclone. Glass drains from the cyclone section through a notch in the back baffle of the cyclone to a sump in the main furnace cavity. In the pilot plant, this sump is drained to a quench tank.

4.7.1.1 Full-Scale Concepts. The full-scale B&W production melter would be designed for a 100 tonne/day glass production capacity. A glass-refining reservoir would be added following the cyclone combustor. The reservoir would be sized to provide ~2 hours of added refining time for the glass at near the melting temperature.

Two variations of the B&W technology are possible. The first option, provided by B&W, uses innovative technology to minimize the offgas volume. The second option, proposed by Fluor, assumes a conventional offgas approach to minimize process and equipment complexity. A number of contributors to offgas volume are equipment selection dependant. These contributors include, but are not limited to, water vapor from drying of the feed stream, decomposition products from the waste and process additives, air in-leakage, intentional air introductions such as in-film coolers or as cover gases, and combustion products from combustion heating.

4.7.1.1.1 Offgas Minimization Concept. Babcock & Wilcox proposed a combustion melter that uses a flue gas recirculation and oxygen substitution system to minimize system offgas volume (Higley 1995a). The melter system is composed of four sub-components: the cyclone melter, the glass-refining reservoir, the waste heat boiler, and a flue gas recirculation system. The flue gas recirculation system includes an integrated flue gas treatment (IFGT) module, a heat recovery system, and a recirculation fan. A process flow diagram for the B&W offgas minimization concept is shown in Figure 4-11. The

Figure 4-11. Process Flow Diagram for Babcock & Wilcox Offgas Minimization Cyclone Combustion Melter Concept.



waste heat boiler cools the melter offgas to 200 to 260 °C without adding air or water vapor to the offgas stream. Dimensions of the individual pieces are presented in Table 4-13.

The cyclone melter, glass reservoir, and waste heat boiler are modular components that may be installed or removed separately. All would be remotely replaceable. All equipment is water walled for heat removal with tangentially welded tubes in a manner typical for combustion steam generators. The water wall tube system removes ~75% of the waste heat.

The feed slurry is pumped to a four-nozzle header located on top of each cyclone melter. Melter feed pumps are externally located beneath each tank. Babcock & Wilcox also has proposed that the feed injectors be mounted for secant injection to the cyclone to minimize volatile loses. The feed injector was located on the axis of the cyclone during Phase 1 testing.

The melter offgas outlet is expected to be a single connection and is sized to be consistent with the waste heat boiler cross-sectional area. Offgas cooling occurs in the waste heat boiler by heat transfer to water-cooled coils located within the offgas flow path. The first coil would collect aerosols by causing them to condense and plate-out. It is B&W experience that thermal cycling of this coil using soot blowers will cause the hardened buildup to flake off and fall into the melt pool. This assessment is based on B&W experience in designing commercial steam generators for service with low-grade coal and design of kraft recovery furnaces for the pulp and paper industry. The intent would be to make all these cooling coils remotely replaceable.

Table 4-13. Dimensions of Major Equipment Pieces for the Offgas Minimization Concept.

Item	Width (m)	Length (m)	Height (m)
Feed tank	3.7 dia.	--	5
Cyclone melter	3 dia.	4	--
Waste heat boiler	4	9	5
Glass-refining reservoir	*	*	*
Integrated flue gas treatment module	4	9	8
Gas/gas heat exchanger	--	--	--
Recirculation fan	2.5	4	3
Oxygen mix station	Incidental	Incidental	Incidental

*A glass reservoir with a 2-hour hold-up capacity is assumed and would fit within the waste heat boiler envelope.

Offgas from the waste heat boiler goes to an air-to-air heat exchanger where it is further cooled and then sent to the IFGT module. The IFGT module integrates water-cooled coils with a spray system to provide evaporative cooling and gas scrubbing. A demister is an integral part of the IFGT module. The scrubbed offgas enters the low-pressure side of the recirculation fan. Twenty percent of the flow is diverted to the melter offgas system. The rest of the flow is reheated in the air-to-air heat exchanger, makeup oxygen is added, and the recirculated gas is recycled to the cyclone as combustion air. The balance of the melter offgas system consists of a scrubber and high-efficiency particulate air (HEPA) filters.

4.7.1.1.2 Equipment Minimization Concept. This concept limits the melter components to the cyclone, the glass reservoir, and the previously discussed feed system. The waste heat boiler and the flue gas recirculation system are replaced with offgas system components more typical of nuclear process facilities. This replacement equipment includes a spray tower, a venturi scrubber, and HEPA filtration.

4.7.1.2 Technical Issues. The B&W technology exhibits some unique advantages relative to traditional melting processes. However, deploying the technology to vitrify the low-level tank waste requires resolution of numerous development and engineering issues within the TWRS program schedule. The number and extent of these issues impose more risk than is resident in Joule-heated melter technology. Resolution of these issues would require an aggressive testing and engineering schedule. Several identified technical issues are as follows.

Control of Entrainment Losses--Entrainment losses to the offgas system during B&W Phase 1 testing were ~7% to 10% of the feed and the highest entrainment losses observed during Phase 1 testing. Babcock & Wilcox expects that entrainment losses can be significantly reduced by making changes in the cyclone operation and equipment configuration. Modification of the feed injector nozzle to eliminate fine droplets and ensure that the feed is delivered to the cyclone wall before becoming entrained in the high-velocity combustion gases within the cyclone will likely be a key factor in reducing entrainment losses.

Component Volatility--Several of the waste components (Na, Cs, F, Cl, I, and Tc) and glass-former additive B are volatile at vitrification temperatures. As discussed in Section 6.0, the B&W test had among the highest volatile component losses observed during Phase 1 testing. The high differential between the combustion temperature (1600 °C at cyclone exit) and the glass melting temperature on the cyclone wall may have contributed to volatile losses. Babcock & Wilcox believes that more favorable operating characteristics will be obtained in a full-scale cyclone such that substantial reduction in the gas flow to glass ratio can be obtained resulting in lower volatility. Babcock & Wilcox also proposes to relocate the position of the feed injector from an axial position to a secant position and expects this modification to reduce volatile losses.

Glass Composition Control--The glass produced during Phase 1 testing was significantly depleted in Na and B due to volatile losses. The use of a borosilicate glass formulation may have contributed to this. For combustion

melting with the B&W melter to be viable for LLW vitrification, recycle of entrained and volatile species and process control to consistently achieve a target glass formulation need to developed and demonstrated.

Homogeneity of Glass--The glass produced during Phase 1 testing was visually inhomogeneous. Some of this inhomogeneity was due to contamination from the furnace refractory, but also included unreacted glass-former particles and heavy cords. A high degree of inhomogeneity and incomplete reaction with glass formers is a concern because these characteristics will likely have an adverse affect on product durability. Longer glass residence times in the larger full-scale cyclone furnace are expected to improve glass homogeneity. In its full-scale concept, B&W also has included a glass-refining reservoir following the cyclone to produce a more homogeneous glass.

Energy Efficiency and Volume of Offgas--Preliminary technical information reports provided by B&W indicate that the process requires ~58 GJ/tonne of glass. Cold-top Joule-heated melters are considerably more energy efficient. For comparison, energy consumption during the Duratek DM-1000 Phase 1 test, including main electrodes, plenum heaters, and discharge heaters, was ~7 GJ/tonne (1.9 MW·h/tonne). Energy consumption for larger commercial Joule-heated melters is typically on the order of 3 GJ/tonne. Energy consumption of the B&W melter is a concern primarily because offgas volume is directly related to energy consumption. Discharging of waste heat is also a concern.

Refractory Selection--Extensive erosion of the cyclone refractory lining occurred during Phase 1 testing as indicated by inclusions in the product glass and post-test inspection of the cyclone combustor. With the exception of a small test area, all glass contact surfaces of the melter were lined with Plibrico[1] Special 85-S. The small test area was lined with Shamrock[2] 881. The Shamrock 881 was noticeably more resistant to corrosion than was the Plibrico refractory. The practice on commercial cyclones is to let slag replace the refractory as it is eroded away. If the steady-state glass thickness is thinner than desired, alternate stud patterns can be installed to retain more material.

Full-Scale Production Rate Uncertainty--The production rate demonstrated during Phase 1 testing in the B&W small boiler simulator (SBS) pilot test facility was 0.6 to 0.9 tonne/day glass at 5.3 GJ/h (138 to 207 GJ/tonne). The B&W staff believes, based on experience with other materials and further SBS testing, that a production rate of 1.5 tonne/day glass at 5.3 GJ/h (85 GJ/tonne) can be achieved in the SBS pilot plant. The design basis for a full-scale unit provided by B&W would process 100 tonne/day at 240 GJ/h (58 GJ/tonne). The approximate factor of 3 improvement in energy requirement per tonne of glass scaling up from the Phase 1 test results to the full-scale design basis remains to be demonstrated.

Schedule--The B&W cyclone melting technology lacks several features necessary to deploy cyclone combustion technology in an LLW radioactive waste vitrification application. The FY 1994 baseline plan called for construction

[1]Plibrico is a trademark of the Plibrico Company.

[2]Shamrock is a trademark of the North American Refractory Company.

of the LLW vitrification facility to be started in December 1997 and be completed by December 2003. It should be assumed that concurrent testing and engineering of the melter will be needed to deploy the B&W technology in the TWRS LLW vitrification facility and meet this schedule.

4.7.1.3 Technology Strengths. The B&W cyclone melter exhibits a number of characteristics that are desirable in the proposed application.

- Size--The B&W cyclone technology could provide a modular melter design that is smaller than conventional Joule-heated melters. This would be an advantage to the facility layout and during removal and replacement of the melter.

- Process Rate--The TWRS strategy assumes two 100 tonne/day process lines are used. The B&W technology is amenable to scaling up to large units capable of producing 100 to 200 tonne/day of glass. Reducing the number of parallel process lines greatly reduces facility and operating costs.

- Self-Draining--The cyclone is self-draining (it does not require operation of a drain valve) which is an advantage in failed melter scenarios. The melter also can be kept hot during draining without special equipment.

- Passive Design--The cyclone is a passive piece of equipment without consumable parts or many movable parts.

- Maintenance--The technical information report provided by B&W (Higley 1995a) indicates a long operating life can be achieved by using the best of the available construction techniques.

- Equipment Reliability--To date, the concepts for implementation of the B&W cyclone melter have been developed by the combustion engineering staff. The B&W nuclear division has had only a cursory involvement. In lieu of a equipment reliability report, B&W provided a copy of findings from a recent users' group meeting. These findings provide evidence that the latest generation of cyclones melters has been in combustion service for more than 7 years without maintenance.

- Restart Capability--The melter can be allowed to go cold and then restarted without special procedures or equipment. This is particularly desirable because restart after loss of power is a concern for other melters and because feed availability may be a problem for the LLW vitrification facility.

- Glass Formulation Flexibility--Glass-melt electrical conductivity is not a limitation on glass formulation as it is with Joule-heated melter technologies.

- Glass Redox--The B&W melter is flexible with respect to reduction-oxidation chemistry of the glass. A reducing environment tends to partition Tc into the glass. An oxidizing environment will partition Tc into the offgas stream. Depending on the overall TWRS

strategy and systems engineering analysis of the available options, it may be advantageous to partition Tc into the offgas for recovery and diversion to the HLW glass melter.

4.7.2 Phase 1 Testing

Phase 1 testing was conducted by the B&W Research and Development Division at Alliance, Ohio. The test setup and testing details are described in the B&W Phase 1 test plan (WHC-SD-WM-VI-018 [Higley 1995b]). Testing consisted of a series of six SBS scoping tests followed by the 24-hour demonstration test. The scoping tests were used to establish optimum operating conditions for the 24-hour demonstration test. Each scoping test was ~4 to 6 hours long and all were completed in a 2-week time period preceding the demonstration test.

Some difficulties were experienced at the beginning of the 24-hour demonstration. However, after ~1 day of intermittent operation and adjustments, the 24-hour demonstration was conducted under continuous steady-state operating conditions at a slurry feed rate of 45 kg/h (26 kg/h potential glass production rate) without further difficulties. The slurry feed rate was increased to 57 kg/h and then to 68 kg/h at the end of the 24-hour demonstration, resulting in ~28 hours of continuous operation during the demonstration.

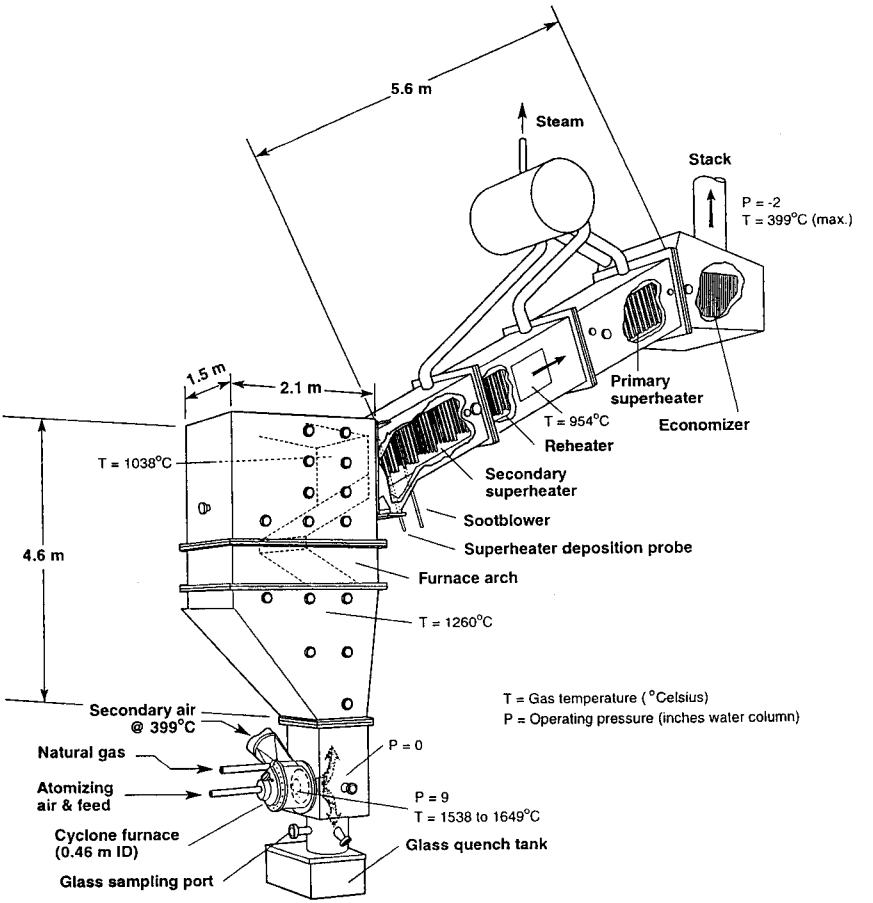
4.7.2.1 Test Facilities. The Phase 1 demonstration test was run in the SBS at the B&W pilot-plant facility. The SBS is rated at 6.3 GJ/h (6 million Btu/h) and includes the main features found in a power plant furnace. Specifically, the SBS includes the cyclone furnace, a sump and water quench tank for collection of molten ash slag, a furnace plenum, and a steam generation tube array (Figure 4-12). A feed injection system was added for the Phase 1 test.

A schematic of the feed system is presented in Figure 4-13. Slurry feed was made up in drums and transferred to a feed tank. A Moyno pump was used to pump the prepared feed into the furnace. The feed mixture was injected into the cyclone furnace through a specially designed injector/atomizer that used high-pressure air to disperse the slurry and spray it onto the cyclone wall. Glass drained from the cyclone furnace to a sump below the furnace plenum and then to a quench tank via a bottom drain in the sump.

The cyclone furnace was fired by natural gas with a small amount of excess air to provide oxidizing conditions during Phase 1 testing. The waste feed contained no reductant additives and was therefore also oxidizing by its composition. Preheated air entered the cyclone tangentially at the 11:00 position viewed from the front. Natural gas was introduced at a point just past where the air was added. Although the SBS pilot plant has the capability to use flue gas recirculation and oxygen substitution to minimize offgas volume, Phase 1 testing did not include the flue gas recirculation or oxygen substitution and a direct air supply was used for combustion.

4.7.2.2 Feed Preparation and Glass Formulation. Babcock & Wilcox used the PNNL-developed LD6-5510 target glass composition for Phase 1 testing. The feed mix used in the test consisted of waste simulant, microsilica, fine

Figure 4-12. Babcock & Wilcox Small Boiler Simulator Pilot Plant as Configured for Low-Level Waste Vitrification.



silica sand, boric acid, limestone, and hydrated alumina ($Al_2O_3 \cdot 3H_2O$). Feed rheology was adjusted to achieve a stable non-settling slurry by adjusting the ratio of microsilica to silica sand. Several feed formulations were tested on a laboratory scale to identify a formulation with the desired rheology. A 30:70 ratio of microsilica to fine sand was used for the scoping and demonstration tests.

Feed batches were prepared in 55-gal (208-L) barrels and mixed by tumbling with a drum mixer (Figure 4-13). The batch formulation for a single barrel feed slurry batch is presented in Table 4-14.

4.7.2.3 Test Monitoring and Sampling. The B&W cyclone melter test was monitored through collection of equipment operating parameters and material samples. Operating parameters were monitored by automatic data acquisition, manual data readings, and manual system measurements. Tables 4-15 and 4-16 summarize the equipment operating parameters and the measurement methods.

Samples were collected at various points in the system to establish the process mass balance and to evaluate process control. Grab samples were collected from the waste feed stream and glass product stream at 2-hour intervals during the 24-hour demonstration test. Isokinetic samples of stack gas particulates were taken at the convective pass exit and at the baghouse exit according to EPA Method 5 protocols. An Anderson emissions parameter analyzer was used to determine the moisture content of the offgas stream. Total particulates and acid gases were captured using a Method 26 impinger train. Volatile metals were captured on a Method 29 train. A cascade impactor was used to establish particle size distribution.

4.7.2.4 Test Chronology. Preparation for the test included relining the cyclone and furnace with new refractory and running a series of six scoping tests. The scoping tests were designed to establish preferred operating parameters for the 24-hour demonstration. The run plan was based on starting the cyclone burner early in the morning on October 12, 1994, and initiating the 24-hour demonstration test by late morning. Because of the difficulties encountered during the test startup and the required adjustments, initiation of the 24-hour demonstration run was delayed ~1 day.

October 12, 1994

0405 Cyclone start up initiated.

0520 Natural gas ignited at 1,500 $stdft^3/min$.

0634 Cyclone burner at full load.

0710 The feed was started at 34 kg/h and increased to 68 kg/h within 30 minutes. After exiting the cyclone, the glass cooled to the temperature in the lower furnace. The cooled glass flowed slowly and tended to bridge the glass tap to the quench tank. However, as the glass inventory in the lower furnace increased, the glass tended to fall under its own weight into the quench tank.

0900 Instrument calibration and collection of baseline data complete.

Figure 4-13. Babcock & Wilcox Small Boiler Simulator Feed System Schematic.

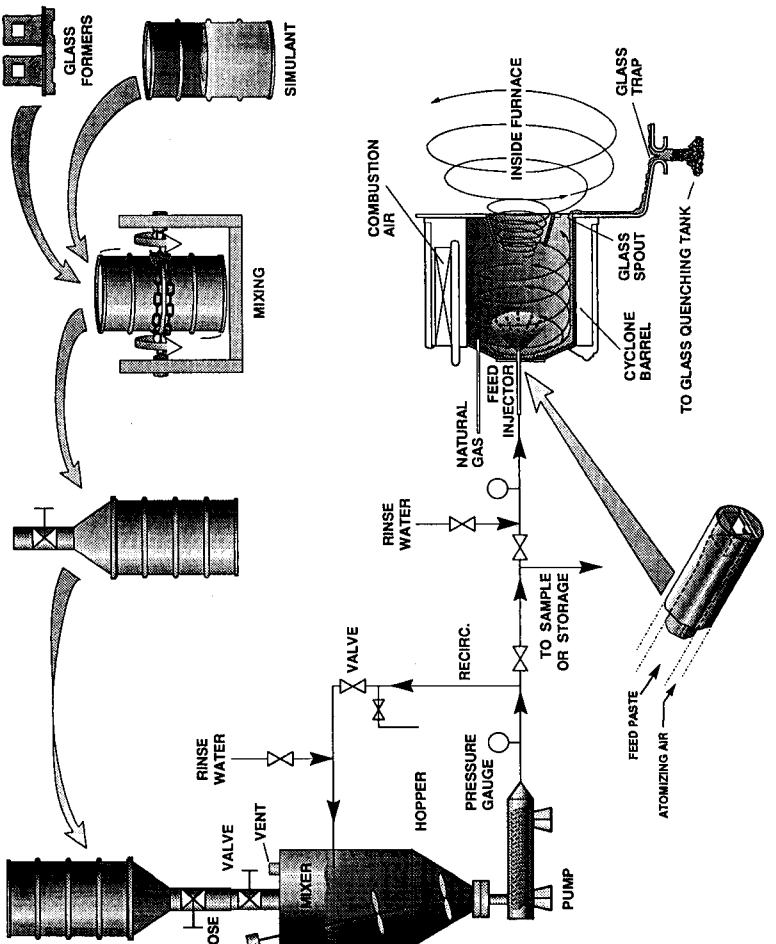


Table 4-14. Mass Basis of Batch Formulation.

Batch material	Weight (kg)	Oxide	Oxide weight (kg)	Total wt% in glass
Low-level waste simulant (1.44 kg/L)	117.94	Na_2O	25.38	19.72
		K_2O	1.93	1.61
		Al_2O_3	4.26	10.18
		Other	2.16	1.75
Hydrated alumina	13.44	Al_2O_3	8.74	--
		Na_2O	0.07	--
		Fe_2O_3	0.08	0.13
Boric acid	11.46	B_2O_3	6.43	4.97
Limestone	11.84	CaO	6.43	5.06
Microsilica	22.58	SiO_2	21.98	56.58
		Al_2O_3	0.14	--
		Fe_2O_3	0.09	--
		CaO	0.13	--
		Na_2O	0.09	--
		K_2O	0.15	--
Fine sand	51.45	SiO_2	51.29	--
		Al_2O_3	0.05	--
		Other	0.11	--
Totals	228.71	--	129.51	100.00

1222 Feed was shut off to repair a broken seal in the cyclone view port. The seal was repaired and the accumulated solids were allowed to melt out.

1530 Feeding at 45 kg/h started.

1830 Feeding was stopped. Molten glass was tapping very well. However, at ~1730 the secondary air dampers began to plug from molten glass being carried around the cyclone. Secondary air is normally introduced at 370 °C. The secondary air inlet is a cool area of the cyclone. A decision was made to modify the operation to rectify this problem.

Table 4-15. Continuously Monitored Test Parameters.

Test parameter	Method
Flow rates	
Combustion air - cyclone, reburners, overfire	ASME orifices
Natural gas - cyclone, reburners	ASME orifices
Feed input rates	Calibrated positive displacement pump
Feed dispensing air flow rate	ASME orifice
Temperatures	
Cyclone/cyclone exit gas temperature	Optical pyrometry
Cyclone glass temperature	Optical pyrometry
Cyclone water jacket temperatures	Type K thermocouple
Gas species concentrations (after convective pass)	
O_2	Beckman Model 755 Analyzer (paramagnetic)
CO_2, CO	Beckman Model 864 Analyzer
NO_x	Beckman Model 951A Analyzer (chemiluminescent)
SO_2	Anarad Model AR-30 Analyzer (ultraviolet absorption)
Particle concentration	
Stack opacity	Light extinction
Other continuously monitored derived quantities	
Total heat input	Calculated
Cyclone exit O_2	Calculated
Cyclone exit mass and volume flow	Calculated

ASME = American Society of Mechanical Engineers

2045 A gas line was connected to small inlets just above the secondary air inlet dampers. These gas injection inlets were fabricated and installed on the system as a result of previous tests. Combustion in this area increased the heat release rate in the vicinity of the secondary air inlet and front wall where the feed injector was mounted. About 20% of the natural gas being consumed by the cyclone combustor was diverted to this supply line.

Table 4-16. Manually Collected Data.

Test parameter	Sampling frequency	Instrument
Furnace exit temperature	Scoping tests - two times 24-hour test - three times	Type K high-velocity thermocouple
Cyclone\cyclone exit gas temperature	Every 4 hours	Type B high-velocity thermocouple
Cyclone water jacket flow	Hourly	Cumulative volumetric meter

2300 The cyclone and furnace were drained of glass accumulation and turned down to idle to allow servicing and cleaning of view ports.

October 13, 1994

0205 Combustion re-initiated.

0645 Cyclone brought up to full service.

0845 Instrumentation checks complete and returned to service.

0913 Feed was started at 34 kg/h. Temperatures on the cyclone barrel surface were measured at 1340 to 1430 °C.

0945 A safety interlock on a cooling water supply line shut off the natural gas supply. Feeding terminated. Gas supply was restored.

1140 Instrumentation restored to service and feed rate increased to 45 kg/h for start of the 24-hour demonstration test.

1230 Molten glass began to tap through the lower furnace into the quench tank.

1330 Collected first glass and feed grab sample of 24-hour demonstration test.

1344-1414 Collected first Method 5 offgas sample.

October 14, 1994

1235 Feed rate increased to 57 kg/h.

1310 Feed rate increased to 68 kg/h. Visual appearance of the glass has improved. Streaking of glass, although still readily apparent, appears to have decreased.

1540 Slurry feed terminated.

1654 End of test instrumentation checks completed.

1655 Energy load to cyclone reduced.

1740 Natural gas supply shut off.

1830 Supply fans and water shut off.

1845 Shut down (except for exhaust fans).

A post-test inspection was conducted after the cyclone furnace had cooled. Refractory wear and damage to the feed injector-atomizer were evident.

4.7.3 Results and Observations

Once the startup difficulties of the first day were overcome, the melter was continuously operated for 28 hours without interruption. Results and observations during the demonstration test operations and post-test inspection results are summarized as follows.

4.7.3.1 Demonstration Test Operations. The melter was operated at a feed rate of 45.5 kg/h for 24.9 hours, followed by 0.6 hour at 56.8 kg/h and 2.5 hours at 68.2 kg/h. Assuming a value of 0.5643 kg glass per kg feed (Higley 1995c), and no process losses (entrainment, volatility, and holdup in the melter), these feed rate and time data imply a potential glass production of 752 kg for the test. A total of 576 kg of glass were collected in the quench tank during the 28-hour demonstration test, suggesting that 23.4% of the potential glass-forming components were lost to the offgas system or otherwise held up in the melter.

The energy input during the test varied from 5.2 to 5.3 GJ/h (4.9 to 5 million Btu/h). Process control parameters (fuel and air), as well as the offgas flow rate, varied <2% during the demonstration run. During the demonstration, the cyclone was operated at full power but at a feed rate below the projected potential.

Because dried feed accumulated as 'stalagmites' hanging off the injector tube during the demonstration test run, the feed injector was periodically rapidly pushed in and pulled out during the run to break loose these accumulated solids. Babcock & Wilcox recommends that the feed injector(s) be moved to the combustion air inlet installed in a secant position to reduce feed buildup on the injectors.

Buildup of molten glass on the combustion air inlet resulted in globs of molten glass falling and interfering with the feed atomizer. The combustion air inlet is a cool spot in the cyclone. This cool spot was identified as a contributing factor in the formation of the glass globs. The problem was resolved by adding fuel just before the air inlet to increase the local temperature, changing the atomizer spray direction, and reducing the feed rate to 45 kg/h for the 24-hour demonstration test. With these changes, the test

ran without interruption. Increasing the feed rate to 57 kg/h and then to 68 kg/h for 4 hours following the 24 hours of operation at a 45 kg/h feed rate did not appear to be a problem after these adjustments.

4.7.3.2 Post-Test Inspection. A post-test inspection was conducted after the test was completed and the cyclone had cooled. Before Phase 1 testing, all glass contact surfaces within the melter were relined with Plibrico Special 85-S refractory cement (~85% Al_2O_3), except for a small test area in the cyclone that was lined with Shamrock 881 (Cr_2O_3-Al_2O_3) refractory. Significant erosion of the Plibrico Special 85-S refractory occurred during the demonstration. Unmelted grains of the refractory material also were noted in the product glass samples. The Shamrock refractory was noticeably more resistant to erosion than was the Plibrico refractory. Heavy refractory wear occurred on the furnace lining opposite the cyclone and in the throat area of the cyclone where the refractory was worn to just above the top of the metal studs. The practice on commercial cyclones is to let the refractory be replaced by slag as it is removed. If the steady-state glass skull thickness is thinner than desired, alternate stud patterns can be installed to retain more material. The wear on the wall opposite the cyclone was caused by exposure to hot high-velocity gases exiting the cyclone. In a full-scale installation, less wear is expected because the distance to the wall is greater than exists in the pilot-plant cyclone.

The tip of the atomizing injector was partially burned off. The feed injector tip was fabricated from tungsten-carbide. The portion of the injector that melted was ~1.3 by 1.9 cm. As a result, the air flow increased and the intended spray pattern may have been disrupted. This could have resulted in increased entrainment carryover. It is believed that the damage occurred during startup for the 24-hour test on October 13, 1994, because the injector air flow rate was ~30% higher than the baseline data throughout the test. Moving the feed injector to the secondary air inlet where the local temperature is 400 °C rather than 1600 °C would help protect the injector from damage.

5.0 PRODUCT GLASS EVALUATION

This section describes the properties and characteristics of the target glass formulations selected by each vendor and compares them with the actual glasses produced during Phase 1 testing. This section also includes a discussion of target glass formulations as well as the independent analytical and glass characterization resources used. Each vendor's product is discussed in terms of major component consistency, minor component retention, homogeneity, and product quality with respect to those characteristics for the desired target glasses.

5.1 PRODUCT REQUIREMENTS

Two requirements were placed on the product glass (Wilson 1994). First, the glass should have a waste loading (weight percent of glass derived from the LLW simulant) of ~25%. Second, the glass formulation should be reasonably durable with a Na normalized leach rate of 1 g/m^2/day or less measured by PCT Method A (ASTM 1994) at 90 °C. The PCT durability requirement, which is approximately equivalent to that of the SRS 'environmental assessment glass' used as a benchmark for the HLW glass durability requirement (DOE 1994), was selected because it is a known readily achievable durability requirement, and at the time of Phase 1 testing, durability and performance requirements for Hanford Site LLW glasses had not yet been established.

During Phase 1 testing, each vendor was to demonstrate its ability to produce a homogeneous glass of consistent composition meeting these requirements using the LLW simulant supplied by WHC. The product was expected to be fully reacted and have a consistent composition and quality with a minimum of inhomogeneities such as cords, stones, devitrification, and/or other inclusions. Complete refining to remove all seeds (small bubbles) was not expected.

5.2 TARGET GLASS FORMULATIONS

Vendors could choose from five preapproved glass formulations developed for Phase 1 testing by PNNL, or develop their own glass formulation. The target DSSF simulant formulation normalized to 10*M* Na concentration was assumed by the vendors for the purpose of glass formulation. The target DSSF simulant composition on a calcined solids basis is presented in Table 5-1. Most vendors also used the target simulant composition as a basis for melter feed batch calculations for feed makeup based on either volume or weight of simulant and weight of glass-former additives.

Target glass compositions selected or developed by each vendor are presented in Table 5-2 along with waste loading, melting temperature (T_m at 100 poise viscosity) and PCT durability data. These are the 'qualification' target glass formulations selected by the vendors for approval. In some

Table 5-1. Double-Shell Slurry Feed Simulant Composition on Anhydrous, Calcined Basis.

Component	Wt%	Component	Wt%
Na_2O	75.22	MnO_2	0.01
K_2O	5.71	MoO_3	0.59
Al_2O_3	12.62	SrO	0.43
CaO	0.01	P_2O_5	0.74
Cr_2O_3	0.16	SO_3	0.83
Cs_2O	0.58	Cl	1.38
Fe_2O_3	0.01	F	1.15
MgO	0.01	I	0.52

cases, actual target compositions used for feed batching varied slightly from these original qualification target compositions. Three of the vendors (Envitco, B&W, and USBM) selected preapproved PNNL glass formulations while four vendors (Duratek, PEI, WSTC, and Vectra) elected to develop their own glass formulations. The temperature-viscosity data and PCT values were measured by PNNL on crucible melts batched from dry oxide and carbonate materials. Viscosities were determined using a rotary viscometer at several different temperatures and the melting temperature for 10 Pa-s (100 poise) viscosity was interpolated from an Arrhenius fit to the empirically measured data. These viscosity and PCT data were provided to the vendors as soon as the data were available. The PCT data were the primary basis for approval of vendor-developed glass formulations. As shown in Table 5-2, all target glass compositions met the <1 g/m^2/day normalized Na release PCT requirement.

5.3 GLASS SAMPLE ANALYSES

A number of glass product samples were collected from each vendor test at different process stages. To provide a fair basis for comparison of product glass and to avoid analytical bias, independent laboratories were used to determine product glass compositions and characteristics for each vendor. The laboratories had experience in characterization of chemically complex glasses and silicate materials and a demonstrated ability to accurately produce high-quality results. Three laboratories were selected: Corning Engineering Laboratory Services (CELS) of Corning, New York; the U.S. Geological Survey (USGS), Branch of Geochemistry, Analytical Chemistry Services Group in Denver, Colorado; and PNNL in Richland, Washington. All three of these laboratories had previously participated in waste glass analytical round-robin exercises.

Table 5-2. Vendor Target Glass Compositions (wt%).

Glass component	Envitco	B&W	USBM	Duratek	PEI	WSTC	Vectra
Na_2O	20.00	20.00	20.00	18.82	18.82	18.82	20.00
K_2O	1.52	1.52	1.52	3.68	1.43	1.43	1.52
Al_2O_3	12.00	10.00	10.00	6.14	6.00	18.22	10.00
B_2O_3	9.00	5.00	5.00	6.15	--	9.45	8.00
CaO	--	5.00	5.00	7.80	9.77	4.65	2.90
MgO	--	--	--	--	--	--	2.10
Fe_2O_3	--	--	--	7.50	1.00	--	1.00
Li_2O	--	--	--	--	--	0.83	--
TiO_2	--	--	--	1.00	--	--	--
ZrO_2	--	--	--	5.09	2.00	2.10	--
SiO_2	55.78	56.78	56.78	42.22	59.23	42.90	52.78
'Other'	1.70	1.70	1.70	1.60	1.75	1.60	1.70
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Waste loading (%)	26.3	26.3	26.3	25.0	25.0	25.0	26.3
PNNL glass	LD4-912	LD6-5510	LD6-5510	--	--	--	--
T_m (°C @ 100 poise)	1325	1296	1296	1096	1327	1215	1224
PCT Na (g/m^2/day)	0.046	0.074	0.074	0.102	0.242	0.034	0.078

B&W = Babcock & Wilcox
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
PCT = Product consistency test
PEI = Penberthy Electromelt International, Inc.
PNNL = Pacific Northwest National Laboratory
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.
WSTC = Westinghouse Science and Technology Center

Product glass and melter feed samples generally were prepared for analysis by a fusion/dissolution sample preparation method. Inductively coupled plasma spectroscopy was generally used for metals analyses. CELS was the primary laboratory for feed and glass compositional analyses with the

other two laboratories providing backup or confirmatory analyses. Confirmatory analyses by X-ray fluorescence also were done. Certain constituents such as halogens were determined by alternate methods including ion chromatography or ion-specific electrode. Glass redox state was measured as the Fe^{+2}/total Fe ratio. The USGS also had capabilities to conduct neutron activation analysis and inductively coupled plasma-mass spectroscopy which were used on an as-needed basis. Neutron activation analysis was used for iodine analysis. Product consistency testing was performed by all three laboratories. A database containing the results of the compositional analyses, redox, and PCT results for all test samples is provided in WHC-SD-WM-DP-131 (Mast 1995).

A combination of polarized light optical microscopy, scanning electron microscopy/electron microprobe analysis, and X-ray diffraction was used to evaluate phase characteristics and homogeneity in the glasses. These techniques identified and characterized features such as cords, devitrification, inclusions or incomplete reactions, and stones, and provided evidence of internal stresses. The microstructural characterizations were performed primarily by USGS and CELS.

5.4 INDIVIDUAL VENDOR GLASS PRODUCT RESULTS

This section compares the vendor glass product compositions with the target compositions and evaluates the consistency, homogeneity, and general glass quality produced by each vendor during Phase 1 testing. While a number of glass samples were collected at various stages during testing for each vendor test, an attempt was made to select glass samples for this evaluation that represented steady-state operations and also were close to, or the same as, samples associated with mass balance evaluations where corresponding melter feed and offgas samples were also analyzed. These samples generally were characterized by at least two of the available analytical laboratories.

Except for PEI and WSTC, melter feed batches were made up based on volume or weight additions of the liquid/slurry DSSF simulant and weights of glass-former additives. PEI and WSTC separately metered simulant and glass-former feed streams, continuously mixing these streams just before injection into the melter. Because of the range of results and uncertainties in the various available simulant analyses (see Section 3.5), most vendors assumed the simulant target composition as the basis for melter feed batch compositions. In addition, other factors, such as solids precipitation from the simulant and failure to get all solids uniformly redispersed into the feed, contributed to differences between vendor target glass compositions and compositions measured for actual product glass test samples. Therefore, for detailed quantitative evaluation of component mass balances during the testing, the reader should refer to mass balance evaluations discussed in Section 6.0 which are based on data from actual melter feed, glass, and offgas sample analyses rather than target compositions.

5.4.1 Envitco

The compositions of two representative glass samples from the Envitco dry feed test are compared with the Envitco target glass composition in Table 5-3.

At ~17.5% Na_2O, the Envitco product glass was deficient in Na_2O compared to the 20% target value. Tie component calculations of volatile component losses based on melter feed and glass analyses data (see Section 6.3) indicate negligible Na volatility loss occurred during melting and Na loss should not have occurred during the feed preparation process. Most of the Na_2O deficiency in the product glass may have been caused by Na deficiency in the Optima Lot 1 simulant used. However, product glass samples from the Duratek DM-100 test, which also used Lot 1 simulant, showed less Na_2O deficiency (~17.8% Na_2O versus 18.82% target). Envitco assumed the 10*M* target simulant composition as the basis for its melter feed batch calculations. Several analyses of the Lot 1 simulant by various laboratories produced results ranging from 8.5*M* to 10.1*M* Na. Four Lot 1 simulant samples taken from different well-stirred drums analyzed by the USBM provided results ranging from 8.74*M* to 8.96*M* Na with a mean value of 8.85*M*, which would account for most of the Envitco glass Na_2O deficiency. Additional factors that may have contributed to Envitco Na_2O deficiency are (1) various analytical errors may have occurred, (2) the 1.45 g/cm^3 simulant density value assumed for batching the simulant by weight may have been high, and (3) the observed fuming from the melter pour steam may have resulted in significant Na_2O and B_2O_3 losses.

Table 5-3. Comparison of Envitco, Inc. Glass with Target Composition.

Oxide	Target composition	Sample 015 C	Sample 028 C/U
Na_2O	20.00	17.7	17.5/17.3
K_2O	1.52	1.35	1.31/1.30
Al_2O_3	12.00	10.7	10.8/10.9
B_2O_3	9.00	8.47	8.38/7.31
CaO	--	0.069	0.057/0.070
MgO	--	0.032	--
Fe_2O_3	0.00/1.00*	0.093	0.68/0.72
TiO_2	--	0.018	0.015/0.025
ZrO_2	--	0.040	0.028/0.026
SiO_2	55.78	57.8	58.6/59.0
Fe^{+2}/Fe	--	0.66	0.56/0.56
PCT pH	10.55	10.2	10.2/9.9
PCT Na (g/m^2/day)	0.046	0.011	0.01/0.028

*1.00% Fe_2O_3 was added to feed Batch UN-6, Sample 015 before feeding UN-6, Sample 028 after starting UN-6 feed.

C = Corning Engineering Laboratory Services analysis
PCT = Product consistency test
U = U.S. Geological Survey laboratory analysis

However, if the pour stream fuming losses were a significant factor, this should have been indicated by the feed/glass tie component calculations which indicated negligible Na_2O loss.

The redox ratio (Fe^{+2}/Fe) for Sample 028 indicates a moderately reduced glass with 56% of the Fe reduced from the Fe^{+3} to the Fe^{+2} state. Sample 028 was taken ~20 hours after feeding the UN-6 feed containing 1 wt% Fe_2O_3 was started and the glass Fe_2O_3 content had increased to ~0.7%. Sample 015 was taken near the end of the UN-57 feed segment before starting the UN-6 feed. No Fe_2O_3 was added to the UN-57 feed and the 0.093% Fe_2O_3 measured in the 015 glass presumably originated from feed component impurities and the trace amount (0.01% oxide basis) included in the target simulant formulation. The redox data indicate that the 100% stoichiometric carbon addition (relative to NO_3/NO_2 reduction) effectively reduced the glass even though the carbon - NO_3/NO_2 reactions occurred primarily in the melter batch blanket rather than during the Bepex feed drying process as originally planned. The effectiveness of the reductant addition is also evident by the negligible wear on the molybdenum electrodes measured during the melter testing.

The measured glass PCT Na release values ranging from 0.01 to 0.028 g/m^2/day were lower than the 0.046 g/m^2/day value measured for target glass composition. This is consistent with the lower 17.5% Na_2O content of the product glass samples, and the higher 1400 to 1450 °C temperatures at which this glass was melted in the melter test, compared to the 1325 °C melting temperature (at 100 poise viscosity) measured for the 20% Na_2O target glass.

Inclusions were not found in the Envitco glass and there was no evidence of devitrification. Glass samples were clear and ranged from light green to green to amber depending on Fe content and redox state. Some faint cords were clear under plane-polarized light, but crossed polarizers revealed anisotropy suggesting internal stress lines. A few small bubbles were observed, but in general, the glass was well-reacted and uniform. Continuous microprobe scans for several diagnostic elements over a distance of up to 1.5 mm did not reveal any discontinuities indicating a chemically homogeneous product.

5.4.2 Vectra

The characteristics of glass samples from the Vectra test are compared to those of the Vectra target glass composition in Table 5-4. Samples 013 and 041 were taken during the slurry feed (MT-2 run) testing. Samples 088, 090, 096, and 098 were taken during the calcined feed melter testing (MT-4 run). Vectra used Lot 2 simulant and assumed the 10*M* Na target simulant composition as the basis for all its melter feed batch calculations. Available analyses for the Lot 2 simulant used by Vectra were more consistent than those obtained on the Lot 1 simulant and indicated a Na concentration of ~10.5*M* for the Lot 2 simulant. The approximate 16% Na_2O product glass sample values are 20% below the 20% Na_2O target level. Mass balance data suggest that approximately one-fourth of this missing Na_2O was due to volatility losses during melting. Factors accounting for the balance of the Na_2O deficiency are uncertain, but may have included batching errors, simulant analyses errors, simulant not representative of original Lot 2 (Optima Batch 3) samples analyzed for simulant acceptance, volatility losses greater than calculated, or failure to incorporate all precipitated solids (primarily $NaNO_3$) during feed batching.

Table 5-4. Comparison of Vectra Technologies, Inc. Glasses with Target Compositions.

Oxide	Target composition	Samples 013/041 C	Samples 088/096 P	Samples 090/098 U
Na_2O	20.00	16.2/15.4	16.3/15.9	16.2/16.1
K_2O	1.52	0.59/0.68	1.97/2.04	0.90/0.90
Al_2O_3	10.00	9.47/9.55	10.28/10.45	9.74/9.73
B_2O_3	8.00	7.28/7.61	7.12/7.22	7.49/7.41
CaO	2.90	2.90/2.96	3.26/2.88	2.94/2.94
MgO	2.10	2.22/2.28	2.07/2.07	2.18/2.19
Fe_2O_3	1.00	1.01/1.00	1.16/0.95	1.03/1.00
TiO_2	--	0.02/0.05	0.02/0.01	0.03/0.02
ZrO_2	--	0.02/0.05	0.04/0.04	0.037/0.037
SiO_2	52.78	58.8/58.3	54.0/53.8	57.1/57.2
Fe^{+2}/Fe	--	0.95/0.98	--	1.04/1.11
PCT pH	11.12	10.50/10.40	10.38/10.37	10.33/10.29
PCT Na (g/m^2/day)	0.078	0.014/0.012	0.032/0.031	0.032/0.029

C = Corning Engineering Laboratory Services analysis
P = Pacific Northwest National Laboratory analysis
PCT = Product consistency test
U = U.S. Geological Survey laboratory analysis

The Vectra melt was reducing as indicated by essentially all the Fe being in the Fe^{+2} ferrous state. Redox ratios (Fe^{+2}/Fe) >1.00 reported by USGS for Samples 090 and 098 are due to analytical uncertainties where Fe^{+2} was measured by acid dissolution followed by titration and total Fe was determined by X-ray fluorescence. The reduced state of the glass likely indicates excessive additions of sucrose reductant. The durability of product glass samples was better than the target glass composition value, which is consistent with the lower Na_2O content and higher melting temperature for actual product glass composition. Melting temperatures during the slurry feed and calcined feed test segments when these samples were taken ranged from 1400 to 1450 °C versus a 1224 °C melting temperature measured for the target glass composition at 10 Pa-s (100 poise) viscosity.

Some of the Vectra glass samples exhibited abundant cords, but cords were absent in other samples. Occasional bubbles were present and inclusions were <1 vol%. Inclusions were primarily Mo metal or Mo sulfide (Mo and S characteristic X-ray lines overlap) which is consistent with the reduced state of the melt and the amount of molybdenum electrode wear observed. No evidence

of devitrification was observed and microprobe line scans up 2 mm indicated no compositional fluctuations. The glasses appeared to be well mixed and reacted, but reduced. Glass samples were transparent and dark green.

5.4.3 Duratek

The characteristics of glass samples from the Duratek tests are compared to those of the Duratek target glass composition in Table 5-5. Duratek used slurry feed and two different melters in its tests. Samples labeled 023 in Table 5-5 are from the DM-100 test and samples labeled 110 are from the DM-1000 test. The DM-100 test used Lot 1 simulant. The first seven feed batches of the DM-1000 test were used to flush a prior glass composition from the melter. The first of these feed batches used four drums of Lot 1 simulant. The DM-1000 feed Batches 2 through 5 each used four drums of Lot 2 simulant. Batch 6 used two drums each of Lot 1 and Lot 2 simulant, followed by Batch 7 using two drums of Lot 1 and one drum of Lot 2 simulant. Feed Batches 8 through 10 were used during the 'steady-state' DM-1000 test run. Batches 8 and 9 used two drums each of Lot 1 and Lot 2 simulant, and Batch 10 used three drums of Lot 1 and one drum of Lot 2 simulant.

Table 5-5. Comparison of GTS Duratek, Inc. Glass Samples with Target Values.

Oxide	Target composition	023 P/U (DM-100)	110 C/P/U (DM-1000)
Na_2O	18.82	18.1/17.5	17.7/17.3/17.8
K_2O	3.68	3.00/3.37	3.45/2.77/3.38
Al_2O_3	6.14	6.36/6.45	6.24/7.60/6.42
B_2O_3	6.15	7.05/6.28	6.46/5.97/6.21
CaO	7.80	8.50/8.36	7.10/7.72/7.77
MgO	--	0.53/0.51	0.31/0.27/0.34
Fe_2O_3	7.50	7.70/7.46	6.26/6.05/6.25
TiO_2	1.00	0.91/0.91	0.83/0.77/0.83
ZrO_2	5.09	3.79/3.84	4.52/4.33/4.43
SiO_2	42.22	42.0/43.0	40.8/40.7/42.3
Fe^{+2}/Fe	--	0.10/0.11	<0.0004/0.0015/--
PCT pH	11.46	--/11.5	11.5/11.3/--
PCT Na (g/m^2/day)	0.102	0.102/0.106	0.036/0.081

C = Corning Engineering Laboratory Services analysis
P = Pacific Northwest National Laboratory analysis
PCT = Product consistency test
U = U.S. Geological Survey laboratory analysis

In general, analyses of the Duratek glass samples agreed very well with their target glass composition. Duratek assumed target 10.0*M* simulant composition values for all batch calculations. Mass balance results indicated negligible Na_2O volatility loss during the testing by Duratek. The average Na_2O content measured by PNNL for the last three samples taken during the DM-100 test was 17.99%. The average (eight analyses) DM-1000 glass Na_2O content was 17.63%. The slightly below target ZrO_2 (added as zircon, $ZrO_2 \cdot SiO_2$) concentrations may be explained by unreacted zircon particles observed in glass samples and failure to uniformly dissolve zircon inclusions during analytical sample preparation.

The maximum Fe^{+2}/Fe redox ratio measured on DM-100 glass samples was 0.11. For the DM-1000 test, the maximum redox ratio was 0.0015 with most measurements reported as <0.0004. The Duratek glass samples, along with those from the WSTC test, were the most oxidized glasses in terms of Fe^{+2}/Fe ratio produced during Phase 1 testing. Although urea reductant additive was included in DM-100 and DM-1000 test slurry feeds for NO_2/NO_3 reduction, the use of air bubbling from the bottom of the melter glass tank in both tests apparently prevented substantial reduction of the glass. Durabilities for the DM-100 glass samples were approximately equal to that measured for the target glass composition. Durabilities measured on the DM-1000 glass samples were somewhat better than those measured on the target glass composition.

The Duratek glass samples exhibited faint cords and no devitrification. Inclusions ranged up to 2 vol% and were primarily unreacted zircon grains that had Na-rich reaction rims. Zircon was used as part of the glass-former additive mixture and apparently was only partly reacted and did not completely dissolve in the melt. There were also trace amounts of aluminous stones and unmelted quartz grains as inclusions. A high level of small bubbles also was present in most glasses. The glass appeared to be well mixed, but not completely reacted.

5.4.4 USBM

The characteristics of glass samples from the USBM test are compared to those of the USBM target glass composition in Table 5-6. The USBM used Lot 1 simulant. Feed batching was based on a USBM in-house simulant analysis indicating a Na concentration of 9.92. Individual simulant drums were sampled during feed preparation and later analyses of these samples by USBM indicated an average Na concentration of 8.85*M* (Eaton 1995f). Samples 004 and 011 included in Table 5-6 are from the first melter run designated by USBM as Run WHC1. As described in Section 4.5, USBM later conducted two additional melter runs on its own (designated WHC2 and WHC3) that used excess dried feed left over from USBM WHC1. The purpose of USBM WHC2 and USBM WHC3 was to test melter modifications made in an attempt to achieve less-intensive cold-top melting to improve melter mass balance results. Sample WHC3-SP1B data in Table 5-6 are from a USBM WHC3 glass sample analyzed by USBM. Significant reductions in Na_2O, K_2O, and B_2O_3 volatilization losses were achieved in USBM WHC3. A fourth run (USBM WHC4) was later conducted to test additional melter modifications and to demonstrate the melting of dry unreacted and wet unreacted feeds. Results for USBM WHC4 glass samples were unavailable as of this writing.

Table 5-6. Comparison of U.S. Bureau of Mines Samples with Target Values.

Oxide	Target composition	Sample 004 C/U	Sample 011 C/P/U	Sample WHC3-SP1B[a]
Na_2O	20.00	17.1/16.5	16.8/15.4/16.2	18.2
K_2O	1.52	1.03/1.01	0.98/<0.3/0.98	1.25
Al_2O_3	10.00	11.7/11.7	12.5/13.26/12.6	10.22
B_2O_3	5.00	3.13/2.90	2.84/2.53/2.67	4.02
CaO	5.00	6.43/6.38	7.30/6.73/7.34	7.25
MgO	--	0.33/0.31	0.34/0.30/0.31	0.42
Fe_2O_3	1.00[b]	1.03/1.04	1.21/1.13/1.21	1.40[c]
TiO_2	--	0.27/0.28	0.38/0.30/0.40	0.19
ZrO_2	--	0.007/0.006	0.008/<0.01/0.009	0.04
SiO_2	56.78	59.4/58.5	58.9/50.2/57.2	54.55
Fe^{+2}/Fe[d]	--	1.10/1.19	1.13/0.96/1.18	--
PCT pH	11.48	11.3/11.1	11.3/11.1/11.1	--
PCT Na (g/m^2/day)	0.074	0.019/0.052	0.018/0.049/0.046	--

[a]Analysis by the U.S. Bureau of Mines.
[b]Pacific Northwest National Laboratory LD6-5510 glass formulation was adjusted by the U.S. Bureau of Mines to include 1% Fe_2O_3.
[c]Reported as wt% FeO.
[d]Fe^{+2}/Fe >1.00 values attributed to analytical error.

C = Corning Laboratory Services analysis
P = Pacific Northwest National Laboratory analysis
PCT = Product consistency test
U = U.S. Geological Survey laboratory analysis

The USBM glass was highly reduced with essentially all the Fe in the Fe^{+2} ferrous state, which is most likely a result of reduction by the carbon electrodes in this melter. The PCT Na releases measured on the USBM WHC1 glass samples were all below those measured for the target composition, which is consistent with the lower Na_2O and higher Al_2O_3 and SiO_2 contents relative to the target composition. Run USBM WHC1 glass was tapped from the melter at ~1500 °C versus a measured 1296 °C melting temperature at 10 Pa-s (100 poise) viscosity measured for the target glass composition.

Run USBM WHC1 samples contained <1 vol% inclusions, most of which were optically opaque. These opaque inclusions were generally Mo metal or Mo sulfide with particle sizes <3μ. No evidence of devitrification was observed.

The bulk glass was black. Thin fractured chips were translucent with a dark smokey color when observed with back lighting. Numerous faint to heavy cords were present. The cords were enriched in K, Na, Mo, and Fe and depleted in Si, Ca, Al, and Ti relative to the average composition. This glass can be characterized as well reacted, but poorly mixed, cordy, and very reduced.

5.4.5 WSTC

The characteristics of glass samples from the WSTC test are compared in Table 5-7 to those of the qualification target glass composition adjusted to replace 0.5% of Al_2O_3 with Fe_2O_3. Samples 412 and 419 were taken at about the mid-point and three-fourths of the way through the test, respectively. The WSTC used Lot 2 simulant for which acceptance analyses had indicated a Na concentration of ~10.5*M*. The simulant was fed from an outdoor tank during cold weather and a large quantity of solids precipitated under the cold conditions that were difficult to hold in uniform suspension. Although not

Table 5-7. Comparison of Westinghouse Science and Technology Center Glass with Target Glass.

Oxide	Target composition*	Sample 412 C2	Sample 419 C3
Na_2O	18.82	18.2	20.8
K_2O	1.43	0.97	1.07
Al_2O_3	17.72	18.4	17.8
B_2O_3	9.45	7.95	7.46
CaO	4.65	4.34	3.92
MgO	--	0.07	0.06
Fe_2O_3	0.50	0.62	0.52
Li_2O	0.83	0.81	0.73
TiO_2	--	0.03	0.06
ZrO_2	2.10	2.13	1.93
SiO_2	42.90	37.5	35.5
Fe^{+2}/Fe	--	0.075	<0.011
PCT pH	10.82	10.5	10.8
PCT Na (g/m^2/day)	0.034	0.013	0.027

*Qualification composition adjusted replacing 0.5% of Al_2O_3 with Fe_2O_3.

C = Corning Engineering Laboratory Services analysis
PCT = Product consistency test

all the simulant solids were redissolved or resuspended, periodic sampling from the simulant feed line indicated relatively uniform simulant feed composition at 9.88*M* Na during testing (Hendrickson 1995b).

There was considerable uncertainty regarding actual melter feed compositions and mass balances during the WSTC testing. A pre-manufactured frit was separately metered and blended with the simulant before injection as a slurry into the plasma melter tuyere. Simulant and frit feed rates initially were selected based on a 28% target waste oxide loading (21.1% Na_2O) to adjust for an assumed 15% waste oxide volatility. Analyses of periodic slurry samples (mixed simulant and frit) from the melter feed line indicate that the frit feed rate exceeded the initial target frit feed rate early in the test, and then decreased relative to the simulant feed rate as the test progressed. This caused the melter feed waste loading to increase during the test. Although the data are somewhat ambiguous, glass sample analyses and integrated frit feeding data during the test do not support the declining frit feed rate hypothesis. Total glass produced was 1,005 kg (12%) less than the theoretical glass production calculated based on integrated simulant and frit feeding data (Hendrickson 1995b).

The WSTC glass samples, along with those from the Duratek test, were the most oxidized glasses in terms of Fe^{+2}/Fe ratio produced during Phase 1 testing. The PCT Na releases ranged from 0.013 to 0.050 g/m^2/day (five samples) compared to 0.034 g/m^2/day measured on the qualification target glass composition.

Inclusions in the WSTC glass samples were generally <1 vol% of the glass and consisted of traces of Fe-Cr opaques and feldspathic stones. Other inclusions were zircon grains and alumina refractory stones. Some devitrification was observed and was dominantly alkali aluminosilicate, which was not too surprising considering the high alumina content of the target composition. Cords were numerous, heavy, and multilamellar. They were enriched in Al, Zr, Ca, and Fe and depleted in Si and K relative to the bulk glass. The glass was well reacted, but not very well mixed.

5.4.6 B&W

The characteristics of glass samples from the B&W test are compared to those for their target glass composition in Table 5-8. Babcock & Wilcox used Lot 1 simulant and assumed the 10*M* Na target composition for the simulant as the basis for its slurry/paste melter feed batch makeup. An in-house analysis of the simulant indicated a 10.1*M* Na simulant concentration (Higley 1995c). The B&W test appeared to have the greatest Na_2O and B_2O_3 volatility losses observed during Phase 1 testing. Significant refractory dissolution also occurred during testing, which likely accounts for the relatively high Al_2O_3 values. Sample 014 analyzed by CELS may have included an undissolved refractory grain accounting for the 17.2% Al_2O_3 value measured in this analysis. Because of the inhomogeneous appearance of the samples, PNNL remelted its samples before the analysis.

Table 5-8. Comparison of Babcock & Wilcox Glass Samples with Target Values.

Oxide	Target composition	Sample 013 C/U/P[a]	Sample 014 C/P[a]
Na_2O	20.00	14.8/13.4/13.4	14.9/12.5
K_2O	1.52	1.06/0.99/2.84	0.84/3.15
Al_2O_3	10.00	11.9/13.1/12.6	17.2/12.9
B_2O_3	5.00	2.43/1.79/1.62	1.12/1.39
CaO	5.00	5.70/5.61/5.23	6.69/5.14
MgO	--	0.17/0.17/0.24	0.20/0.20
Fe_2O_3	1.00[b]	0.63/0.74/0.58	0.80/0.66
TiO_2	--	0.15/0.18/0.17	0.21/0.17
ZrO_2	--	0.05/0.06/0.06	0.09/0.06
SiO_2	56.78	59.1/63.0/62.7	54.0/63.0
Fe^{+2}/Fe	--	0.62/0.54	0.62
PCT pH	11.48	10.6/10.3/10.6	10.3
PCT Na (g/m^2/day)	0.074	0.014/0.024/0.024	0.010

[a]Pacific Northwest National Laboratory analyses performed on remelted glass samples.
[b]Pacific Northwest National Laboratory LD6-5510 glass formulation was adjusted by Babcock & Wilcox to include 1% Fe_2O_3.

C = Corning Engineering Laboratory Services analysis
P = Pacific Northwest National Laboratory analysis
PCT = Product consistency test
U = U.S. Geological Survey laboratory analysis

The glass samples were moderately reduced with Fe^{+2}/Fe values ranging from 0.468 to 0.62 (seven analyses) suggesting that combustion conditions were slightly reducing. The PCT Na release values were significantly lower than the target glass value, which is consistent with the lower Na_2O, and higher Al_2O_3 and SiO_2 in the test glass samples.

A large amount of inclusions in the B&W product were very inhomogeneous. Generally, the inclusions ranged from 1 to 10 vol% and were locally higher (>10 vol%). Sample inhomogeneity likely accounts for much of the variation in analytical results reported by different laboratories. The inclusions primarily consisted of unreacted SiO_2 grains and refractory components such as chromite, zircon, aluminous refractory grains, and spinels. The product contained heavy cords which were enriched in Fe and Zr and depleted in Si, Ca, and Al. In addition, the B&W product exhibited considerable foam regions and

bubbles. The B&W product can be characterized as inhomogeneous and poorly reacted. The X-ray diffraction patterns showed considerable crystallinity. The B&W melter configuration did not include a glass refining reservoir and residence time in the melter at temperature was short (estimated at ~20 minutes). Melter design modification to include a refining reservoir and longer residence times, and the use of a more durable refractory material for lining the cyclone, would likely improve glass product homogeneity and uniformity.

5.5 MINOR COMPONENT LIMITS

The concentrations of minor components derived principally from the LLW simulant analyzed in two glass samples from each vendor test are presented in Table 5-9. The 'target' values shown in the second column of Table 5-9 are the concentrations that would be expected in the glass based on the target DSSF simulant formulation, assuming 25% waste loading and no losses or other sources of these components. Minor components Cr_2O_3, P_2O_5, SO_4, Cl, I, and F can be particularly troublesome because they have low solubilities in glass and will phase separate in the melter if their solubilities are exceeded. Phosphate and sulphate can separate and accumulate as a low-viscosity molten salt layer that floats on top of the glass pool and is corrosive to refractory and electrode materials. The Cr_2O_3 can precipitate in the glass and accumulate as a settled sludge in the melter. Excess halides (Cl, F, and I) are expected to volatilize. The target concentrations of these minor components derived from the Phase 1 DSSF simulant at 25% waste loading were not expected to significantly exceed their solubilities in the glasses. However, the target concentrations for F, Cl, and SO_4 may be approaching or slightly exceeding solubility limits in some of the glasses. The solubility limit for I is not well characterized, largely due to its high volatility. The Cs_2O and MoO_3 also may volatilize during melting.

The excess Cr_2O_3 in the Vectra and Duratek glasses is likely a result of dissolution of chromia-containing refractories in both of these melters. Excess MoO_3 found in some of the Vectra samples likely results from corrosion of the molybdenum electrodes during the Vectra test. With the exception of SO_3, the Envitco melter, with full dry feed cold-top batch blanket coverage, incorporated most of the volatile components into the glass and was the only test to incorporate most of the iodine. A more detailed evaluation of volatility losses is presented in Section 6.0.

5.6 TOXIC CHARACTERISTIC LEACHING PROCEDURE (TCLP) RESULTS

Toxic characteristic leaching procedure testing was performed by Quanterra Laboratories under subcontract to USGS on composite product glass test samples from Phase 1 testing by Duratek, Envitco, USBM, and Vectra in conjunction with disposal of Phase 1 test residues from these vendors. Results from these TCLP tests are presented in Table 5-10. The WSTC and B&W staff had also earlier performed TCLP testing in conjunction with disposal of test residues from their sites.

Table 5-9. Minor Component Concentrations (wt%) in Vendor Glasses.

Comp.	Target[a]	Envitco	Vectra	Duratek	USBM	WSTC	B&W
Sample		015C/028C	041C/098U	023U/110U	004U/011U	412C/419C	011C/013U
Cr_2O_3	0.04	0.046/0.045	0.28/0.29	0.19/0.175	0.040/0.055	0.036/0.046	0.036/0.056
Cs_2O	0.145	0.14/0.14	0.042/0.076	0.11/0.11	0.055/0.046	0.032/0.034	0.022/0.026
SrO	0.11	0.094/0.093	0.06/0.078	0.10/0.115	0.096/0.10	0.14/0.14	0.089/0.10
MoO_3	0.15	0.14/0.14	0.19/0.13	0.13/0.13	0.080/0.092	0.13/0.16	0.072/0.071
P_2O_5	0.185	0.22/0.22	0.092/0.19	0.21/0.26	0.09/0.12	0.11/0.15	0.16[b]/0.16
SO_3	0.21	0.10/0.12	0.029/<0.12	0.15/0.54	0.31/<0.12	0.15/0.19	<0.12[b]/<0.12
Cl	0.34	0.31/0.27	0.07/0.15	0.12/0.18	0.08/0.06	0.069/0.061	0.01/0.05
F	0.29	0.27/0.34	0.15/0.16	0.07/0.15	0.03/0.04	0.03/0.03	<0.01/0.02
I	0.13	0.118[b]/0.112	0.01/0.025	0.020/0.020	0.008/<0.001	<0.003[b]	0.0095[b]/0.0075

[a]Glass content assuming 10*M* Na target simulant composition, 25% waste loading, and no losses.
[b]Sample 019U for Envitco, Sample 425U for WSTC, Sample 006U for B&W.

B&W = Babcock & Wilcox
C = Corning Engineering Laboratory Services analysis
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
U = U.S. Geological Survey laboratory analysis
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.
WSTC = Westinghouse Science and Technology Center

Table 5-10. Toxic Characteristic Leaching Procedure Results on Composite Glass Samples.

Element	Concentration (mg/L)				
	Limit	Duratek	Envitco	USBM	Vectra
As	0.05	BD	BD	BD	BD
Ba	10.0	0.37	0.31	0.29	0.33
Cd	0.10	BD	BD	BD	BD
Cr	0.50	0.051	0.015	0.014	0.0092
Pb	0.50	0.10	BD	BD	BD
Hg	0.00020	BD	BD	BD	BD
Se	0.25	BD	BD	BD	BD
Ag	0.50	BD	BD	BD	BD

BD = Below detectable
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.

5.7 SUMMARY

Even with the variations in LLW target glass formulations and resulting product glass characteristics, all vendors were able to produce glasses that were significantly more durable than the <1 g/m^2/day normalized Na release PCT requirement for Phase 1 testing. In most cases, the PCT durability values from vendor glasses exceeded the 1 g/m^2/day requirement by 1 order of magnitude or better.

Some vendors did not meet the waste loading requirements based on Na_2O content. Low waste loadings in glasses produced during the Envitco and Duratek tests appear primarily to be the result of assuming the target 10*M* Na concentration for the Lot 1 DSSF simulant used, which now appears to have actually been ~9.0 ± 0.5*M* Na. Feed batching errors may also have contributed to the below-target waste loadings. Assuming 10*M* Na concentration for the Lot 1 simulant also was likely a contributing factor in the below-target waste loadings achieved in the USBM and B&W tests. However, significant Na_2O volatility appeared to occur in the USBM and B&W tests, with the B&W test exhibiting the greatest Na_2O volatility of any of the tests. Significant volatility losses also were observed in the WSTC test where a target slurry feed waste loading of 28% was used to compensate for anticipated volatility losses. However, achieving a consistent target glass composition, and evaluation of the melter mass balance, in the WSTC test was complicated by

apparent poor control of the glass-former frit feed rate during the test. With the exception of the Envitco dry feed test, significant halide losses were observed in all tests.

The best glass quality in terms of uniformity and homogeneity resulted from melter technologies with good mixing and refining capabilities. The least homogeneous product was produced in the B&W test. With the exception of the B&W glass, all other vendor glasses were relatively homogeneous and well reacted. However, grains of unreacted zircon were observed in the Duratek glass, which was otherwise relatively well reacted and homogeneous. The Duratek and WSTC glasses were relatively oxidized with Fe^{+2}/Fe ratios generally <0.1. The Envitco and B&W glasses were moderately reduced with measured Fe^{+2}/Fe ratios ranging from 0.38 to 0.66. The Vectra and USBM glasses were highly reduced with essentially all the Fe measured in the Fe^{+2} ferrous state ($Fe^{+2}/Fe = 1$).

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6.0 OFFGAS AND MASS BALANCE EVALUATION

A review was conducted of the vendor test reports (Hendrickson 1995b, Eaton 1995b and 1995f, Wilson 1996, Higley 1995c, and Stegen 1996) from each Phase 1 vendor test. The information generated, along with data from the WHC test sample analyses database (Mast 1995), was evaluated to estimate the losses due to selective and non-selective mechanisms, assumed to be volatility and entrainment, respectively. These values are combined to provide the total partitioning of elements to the offgas system. Detailed documentation of this evaluation of the Phase 1 testing offgas and melter mass balance results is provided in WHC-SD-WM-ER-517 (Whyatt et al. 1996). In the case of the Vectra test, where some data from dry feeding are reported, primarily data from the slurry feeding are evaluated because this is Vectra's recommended approach. In the case of Envitco, only the dry feed approach is evaluated due to the absence of offgas data and sample analyses results for the slurry feed test segment. The Duratek evaluation is based on the larger DM-1000 melter test.

6.1 MASS BALANCE EVALUATION METHODOLOGY

The total loss from the melter is determined from estimates of the entrainment (non-selective loss) and volatility (selective loss). The conceptual model of the process is that the gross entrainment occurs first and equally entrains all components. The volatility then occurs from the remainder. The percent volatilized in this conceptual model can be determined based only on glass and feed composition with no knowledge of the degree of gross entrainment. The equation used to recombine the volatility and entrainment values to determine the fraction of each component partitioning to the offgas is shown below.

$$L_T = L_e + L_v \left[1 - \frac{L_e}{100} \right]$$

where:

L_t = Percent total loss of component to offgas
L_v = Percent volatile loss of component
L_e = Percent non-selective entrainment of feed material.

Entrainment loss values are based primarily on aerosol sampling using EPA-approved Methods 5 or 29 for components assumed to be non-volatile, but may also include data for material that collects in downstream offgas equipment. Calculational methods used to determine volatility include a 'tie component' calculation based on glass and feed composition to determine selective losses, and/or determination of the mass of volatilized components based on offgas measurements. When selective losses are much greater than the probable errors in the glass and feed analyses, the tie component method is generally more reliable than estimates based on offgas measurements. When the

selective loss is low relative to probable errors in the glass and feed analyses, volatility estimated based on offgas measurements is generally more accurate.

In the tie component method, a component that is known to have little or no volatility at the melter conditions is selected as an internal standard. In addition to being non-volatile, the component should be present in sufficient quantity to allow accurate analytical determination and should not be subject to contamination from non-feed sources such as refractory or electrode corrosion or other sources. Typical tie components selected for these tests include SiO_2, Al_2O_3, Fe_2O_3, CaO, and SrO with the selection depending on the details of the run. The concentration of the volatile component is compared to the tie component in the feed and glass. The equation is shown below.

$$\text{fraction of component volatilized} = \frac{v_f \frac{t_g}{t_f} - v_g}{v_f \frac{t_g}{t_f}}$$

where:

v_f = Mass fraction volatile component in feed
v_g = Mass fraction volatile component in glass
t_f = Mass fraction tie component in feed
t_g = Mass fraction tie component in glass.

Advantages of the tie component method are that it relies only on compositional analysis and does not require accurate measurement of masses of feed and glass materials. Only the concentration ratios of the components of interest to the concentration of the tie component are important, and the accuracy of the results is not affected by loss of volatile components such as water, nitrates, or carbonates from the feed. In addition, non-selective loss mechanisms, such as accumulation, feed spillage, and gross entrainment of the feed, do not affect results. However, errors can be introduced if the melter is not at steady state with respect to a given component due to changes in feed composition. Also, if there is a source of a component other than from the feed (such as refractory or electrode corrosion), the results will reflect this as a smaller than expected or even a negative measurement of volatility.

6.2 ESTIMATES OF GROSS ENTRAINMENT OF FEED

Entrainment refers to material that is physically entrained in the offgas. Entrainment may result from dusting of a dry feed, boiling of wet feed in a cold cap, or a failure of feed to completely segregate from gases for melters such as those at B&W or WSTC. It is assumed that the loss by entrainment is non-selective and equally entrains all components. Selective entrainment is possible, and if present it is included in this evaluation as

volatility. Table 6-1 provides the best estimates of the rate of entrainment. These values are based primarily on aerosol sampling using EPA-approved Methods 5 or 29 but also examine material that collects in downstream offgas equipment. Table 6-1 is organized roughly in the order of the volatilization and entrainment that was observed during testing. In general, the Joule-heated melters show significantly less entrainment than other types of melters.

6.2.1 B&W

The entrainment for the B&W run was the most severe of any melter system. The entrainment value for B&W was determined based on Method 5 sample analyses along with feed sample data and using the average of results obtained using Al_2O_3 and CaO. There is significant uncertainty in this value due to uncertainty in the feed oxide flow rate and glass production. The value for oxide content of the feed was based on the loss on ignition and loss on drying analytical results (46.3%). This value differs significantly from the value used by B&W (56.47%). Also, the value may be biased low due to losses in the convective pass section before the Method 5 sample point.

6.2.2 WSTC

The WSTC entrainment value of 2.7% is obtained by taking the difference between the mass of glass poured and the mass of glass expected. It is assumed that the presence of CaO or Al_2O_3 in the offgas samples is due to entrainment only and the mass fraction of CaO and Al_2O_3 in the Method 5 aerosol samples is representative of the composition of the total carryover. This approach results in estimates of 2.1% and 3.3% based on Al_2O_3 and CaO content, respectively, which averages to 2.7%. The WSTC test report (Hendrickson 1995b) contained a variety of conflicting values for entrainment including 0.2% (p. 2-10), 0.5% (p. 8-31), 0.7% (p. 8-28), 2.0% (p. 7-18), and 2.2% (p. 7-14). It is believed that the 2.7% entrainment value is the best available estimate of gross entrainment.

Table 6-1. Percent Gross Entrainment Estimates.

B&W	WSTC	USBM WHC1	USBM WHC2	USBM WHC3	Vectra	Duratek	Envitco
8.7	2.7	1.2	N/A	N/A	0.6	0.6	0.06

B&W = Babcock & Wilcox
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
N/A = Not available
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.
WHC = Westinghouse Hanford Company
WSTC = Westinghouse Science and Technology Center

6.2.3 USBM

The 1.2% entrainment estimate for the USBM WHC1 test (the WHC1 run) is based on the mass of SiO_2 collected in downstream offgas processing units. An overall mass balance approach suggests a slightly higher value of 1.7%, but the 1.2% figure is believed to be more accurate. Method 5 samples conducted at the furnace outlet generally indicated lower entrainment values of 0.11% to 0.47% based on Al and Ca results. However, these results are discounted in favor of the evaluation of silica located in the offgas system due to the difficulties experienced in the Method 5 samples such as plugged sampling lines and nozzles, constriction, and partial plugging at the melter exit which disturbed sampling conditions. Insufficient data were collected during the USBM WHC2 (the WHC2 run) and USBM WHC3 (the WHC3 run) tests to estimate entrainment losses for these tests. In the absence of other data, it is suggested that the USBM WHC1-based entrainment value be used. However, modifications made to reduce volatile component losses in runs USBM WHC2 and USBM WHC3 also may have resulted in reduced entrainment losses.

6.2.4 Vectra

The value of 0.6% entrainment for the Vectra MT-2 slurry feed test segment is determined based on Method 5 samples and on the glass and feed compositions to estimate total volatile losses. Total mass loss is estimated at 2.4% with 0.6 wt% being by gross entrainment and 1.8% by volatility. The Method 5 data were sufficiently variable that the 0.6 wt% entrainment estimate should be considered a fairly rough estimate. Entrainment data also were available from aerosol samples during the MT-3 run segment when the melter was fed dry batched material formulated to simulate a calcined feed composition, and during the MT-4 run segment when fluid bed calcined feed was run. The entrainment during MT-3 was similar to MT-2 giving an entrainment rate of 0.4% while the entrainment rate during MT-4 was only 0.07%.

6.2.5 Duratek

The Duratek entrainment value of 0.6% was obtained based on an analysis of Method 5 samples for Sr. The Method 5 sampling data provided by VSL-CUA were used rather than the PES data. The PES data were systematically lower which makes the VSL-CUA data more conservative. The more conservative value was selected because the sampling conditions were far from optimum in terms of flow conditions and flow quantification. The entrainment value estimate based on the PES data was 0.1%.

6.2.6 Envitco

Entrainment calculated for the Envitco dry feed test was very low. The 0.05% value was calculated based on the amount of Al detected in the Method 29 samples. A comparison also was made to the total amount of material collected on the Method 29 sample.

6.3 ESTIMATES OF VOLATILE LOSSES OF FEED COMPONENTS

Selective loss of components through volatilization is a somewhat greater concern than gross entrainment for the LLW vitrification systems. Volatility estimates were prepared primarily using the previously described tie component method. The tie components typically used were Al_2O_3, SiO_2, SrO, CaO, and Fe_2O_3. In some cases, one or more tie components could not be used because of analytical problems, or because of contamination of the tie component by other sources such as refractory corrosion. In some cases, Method 5 (or 29) offgas sampling results have been used in place of the tie component analysis because the results are believed to be more accurate.

The volatility estimate results are shown in Table 6-2. Shaded values indicate the components of concern for volatility and for which total loss estimates are later provided in Section 6.4, Table 6-3. Negative values imply that more material was present in the glass than in the feed material. This may occur because of analytical errors, or from contamination of the glass from refractories or other sources.

6.3.1 B&W

In general, the B&W test showed the greatest volatile component selective losses of the melter systems tested. The volatilities were estimated using the tie component method with SrO, SiO_2, and CaO as the tie components. The values provided in Table 6-2 are the average of the three tie calculation results. The tie component calculations used analytical data taken from mass balance test sample sets* 1, 2, 3, and 5.

All measurements of SO_3 in the glass were below USGS detection limits and Corning did not analyze for SO_3. Therefore, the estimate provided for SO_3 volatility is a minimum value based on the USGS detection limit in glass. Better quantification was achieved in some of the other melter tests when Corning later analyzed for SO_3 with a better detection limit. In the analysis of subsequent melter tests, Corning analyzed for SO_3 and achieved much better detection limits.

The P_2O_5 volatility determination was complicated by the feed analysis being consistently below the target values and a source of P_2O_5 from refractory corrosion. The result provided is based on assuming the feed contained the target P concentration and on the highest obtained loss result corresponding to a period of lower refractory corrosion.

The F volatility estimate contains significant uncertainty. Analysis for F in feed samples was problematic. Because of this, feed target values for fluoride were used in place of feed analysis data. Corning glass results were systematically lower than USGS results. The USGS results were used to arrive at the given F volatility value of 92%. Volatile losses calculated for F would be higher if the Corning data were used in place of the USGS data.

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*Mass balance sample sets included simultaneous samples from the melter feed, glass, and offgas streams.

Table 6-2. Weight Percent Selective Loss of Feed Components.

Component	B&W	WSTC	USBM WHC1	USBM WHC2	USBM WHC3	Vectra	Duratek	Envitco
Al_2O_3	-36[a]	-2.5[a]	-5.4[a]	-3[a]	0.49	~0[b]	-0.1	0[b]
B_2O_3	67	22	51	23	18	14	~0[b]	0.14[b]
CaO	-6.5	2.2	-1.5	-5.7	-1.6	2.0	4.9	14
Cl	87	88	82	N/A	97	64	47.8	1 to 13[b]
Cr_2O_3	-76[a]	12	-32[a]	-80[a]	-64[a]	-683[a]	0.6[b]	0[b]
Cs_2O	83	84	63	N/A	39	41	13.2	0.6[b]
F[c]	~92	~91	~91	N/A	~99.7	~15[b]	~53	<0.85[b]
Fe_2O_3	-86[a]	-32	-4.5	2.9	-1.6	0.3	-6.1	0[b]
I	94	>98	95	N/A	N/A	83	82	10
K_2O	51	48	35	-143	25	15	0[b]	0[b]
LiO_2	N/A	2.8	N/A	N/A	N/A	N/A	N/A	N/A
MgO	-29[a]	-13	-25	-46	-74	-2.3	-12.7	2.9
MoO_3	60	24	47	50	45	-49	0.2[b]	0[b]
Na_2O	35	15	21	20	6.5	13	~0[b]	0[b]
P	~41[a]	43	41	-42	54	1.1[b]	N/A[d]	0[b]
S	>51	34	88	~303[d]	94	85	N/A[d]	53
SiO_2	-0.3	11	0	13	-0.5	~0[b]	0	0.8
SrO	10	-0.1	4.0	-4.2	N/A	~0[b]	0[b]	0.10[b]

NOTE: Shaded values indicate components likely to be affected by volatility.

[a] Negative values likely due to refractory corrosion increasing component content in the glass.

[b] Values based on offgas aerosol data; all other values based on tie component method.

[c] Difficulty was experienced in analyzing melter feeds for fluoride and feed targets; fluoride concentrations were used to determine all fluoride volatility results. Uncertainty also may exist with respect to fluoride glass analysis. Therefore, all fluoride results are considered approximate.

[d] Additional detail is provided in text.

B&W = Babcock & Wilcox
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
N/A = Not available
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.
WHC = Westinghouse Hanford Company
WSTC = Westinghouse Science and Technology Center

The iodine volatility was taken as the average of four data points where USGS neutron activation analysis results were available for corresponding feed and glass samples. The individual results ranged from an 88% loss to a 99% loss of iodine.

Alumina, Cr_2O_3, Fe_2O_3, and MgO have negative calculated volatilities most likely because the glass content of these components was increased as a result of refractory and metal corrosion.

6.3.2 WSTC

The WSTC data indicate volatility that is lower than the B&W system for several key components including B_2O_3 and Na_2O. Results were determined based on mass balance sample sets 1, 2, 3, and 4 using tie components Ca and Al. For SO_3, the analysis from sample set 3 was discarded due to suspected analytical error to arrive at the value provided. The measured glass Fe content is well within detection limits and indicates an unidentified source of Fe contamination exists increasing the glass content relative to the feed. The reason for the indicated 11% SiO_2 volatility is uncertain. It is not expected that SiO_2 has any significant volatility. This may be the result of the unsteady mix ratio between waste simulant and glass formers. However, analytical or sampling errors and contamination of the glass with additional Al and Ca as a result of refractory corrosion also may have contributed to the calculated SiO_2 volatility.

Iodine volatility was determined based on neutron activation analysis of one feed sample and one glass sample. The iodine in the glass sample was below detection limits and the value provided was calculated using the analytical 'less than' result.

6.3.3 USBM

Data from the initial USBM WHC1 test indicate very significant volatility of key components such as B_2O_3 (51%), Na_2O (21%), and MoO_3 (47%). The volatility evaluation was complicated, however, by contamination from TH* feed material used at the beginning of the USBM WHC1 run. Results were based on an SiO_2 tie component using average feed and glass concentrations after correcting SiO_2, CaO, Al_2O_3, and TiO_2 for the apparent contamination. The identically zero result for the SiO_2 is a direct result of the selection of SiO_2 as a tie component. Negative volatilities calculated for some components may be related to the addition of TH feed components to the glass.

Calculation of selective component losses by the tie component method for the USBM tests also was complicated by the occasional addition of lime to the melter as a fluxing agent when the glass became too viscous to drain, and by contamination from steel punchings used to start the furnace in later runs. The volatilities were obtained by first adjusting the glass composition to

*Feed material previously melted by Tree Hugger is defined in WHC-SD-WM-VI-030, p. 3-4 (Eaton 1995f).

remove excess Ca and Fe based on the silica and alumina concentrations. The results were taken as the mid-range value of the calculated results using feed analysis and feed targets with SiO_2 and Al_2O_3 tie components.

The 95% iodine volatility result was determined using neutron activation analysis results for six samples of dried and reacted feed and seven glass samples. The feed samples were used to estimate an average feed composition and loss estimates were made based on each glass sample. Loss estimates ranged from 91% to 99%.

As a result of the high component volatilities observed in the USBM WHC1 run, modifications were made to the melter and in the operating conditions intended to reduce volatility. The USBM reduced the voltage and power input for run USBM WHC2, and based on favorable indications, further decreased the power density on the electrodes for USBM WHC3 by increasing the electrode diameter. Significantly lower volatilities for Na_2O, Cs_2O, and B_2O_3 were achieved during these later runs.*

The fluoride loss is based on feed target values rather than analytical feed values. However, because of the large loss, the impact of this assumption is only to increase the fluoride loss to 99.7% compared to 99.5% if feed analysis values are used.

Interestingly, while the losses of alkali metals and B were significantly reduced in the USBM WHC3 run, the volatile losses of halogens are consistently greater in the revised operating conditions. The trend is believed to be real although the mechanistic explanation is unknown. Activation analysis data were unavailable to estimate iodine losses for the USBM WHC2 and USBM WHC3 runs.

6.3.4 Vectra

The Vectra results indicated volatility somewhat similar to the USBM-3 except that halogen losses were much lower. All results in Table 6-2 are evaluated for the slurry feeding method which was the recommended feed method. Values for Cs_2O, K_2O, F, Cl, I, SO_3, and P_2O_5 were obtained based on a SrO tie component. This was done because these minor components (plus SrO) were not in the startup glass and may not have reached steady-state concentrations by the time the MT-2 mass balance period was started. The remaining results are the average of results obtained using CaO, Al_2O_3, Fe_2O_3, and SiO_2 as the tie components.

The results obtained based on Method 5 offgas analyses are adjusted assuming that gross entrainment is 0.6%. In cases where the Method 5 initial result was <0.6%, the result is expressed as ~0. Aerosol sampling results are believed to be biased low due to line losses between the melter and the sample point. However, for some analytes, the aerosol samples provide improved data over the tie component result. The fluoride result was taken from aerosol sample data due to analytical difficulties experienced in the glass for fluoride. The P_2O_5 data were taken from aerosol samples due to uncertainty

*Based on glass sample analyses performed by USBM for runs WHC2 and WHC3.

regarding the actual feed P concentrations. The tie component calculation indicates an excess of P_2O_5 in the glass compared to feed target values. The single feed sample that was analyzed for P indicated an excess of P_2O_5 in the feed. The aerosol-based result is less sensitive to the feed concentration uncertainty. There was a significant discrepancy between the aerosol result and the tie component result for Na_2O. The aerosol result was only 4% Na_2O loss compared to the 13% loss by the tie component result. It was believed that for >10% loss of a major component the tie component calculation was more reliable. However, there is a possibility that the volatility was lower and that the result was related to errors in the feed composition analyses.

The tie component Cr_2O_3 result was -683% which reflects corrosion of refractory and the stainless steel electrode sheaths. Similarly, the tie component analysis result for MoO_3 was -49% which reflects the loss of electrode material. The Method 5 results for these components indicate that 5.6% and 115% of the Cr and Mo feed content, respectively, were volatilized to the offgas (corrected for 0.6 wt% entrainment).

The 83% volatility result for iodine is based on neutron activation analysis of four glass samples using a SrO tie component calculation. Suitable feed samples were unavailable so the feed target values were used for feed iodine content.

In addition to the slurry feeding data, Vectra generated data from feeding of dry batched materials with a composition intended to match a calcined feed (Run MT-3) and from running actual calcined feed (Run MT-4). Because of the short durations, tie component calculations were not possible for these testing periods. However, aerosol sample data were taken and can be used to estimate volatile losses. During Run MT-3, it appeared that the volatility was lower than for slurry feeding. During Run MT-4, it appeared that the volatility was as high or higher than slurry feeding and it appeared that significant unidentified sources of chloride and S were present.

6.3.5 Duratek

The Duratek DM-1000 melter experienced only moderate volatility losses. Results provided in Table 6-2 were, with a few exceptions discussed below, obtained using USGS analyses results for feed and glass and using SiO_2 as a tie component. Corning analytical results for feed were not used because no analysis was available for mixed feed and the simulant analysis indicated a significant deficiency in Al_2O_3 which may have been due to either sampling or analytical error. In the case of MgO, the Corning analytical results were selected because USGS failed to obtain a result greater than detection limits. For the fluoride result, the target feed concentration was used in place of the analytical value due to the analytical problems that were generally experienced for this analyte.

The selective loss values obtained using Method 5 results used the VSL-CUA Method 5 data (rather than the PES data). The values were obtained by adjusting the data to remove the contribution from gross entrainment calculated assuming the Sr content in the Method 5 samples was due entirely to entrainment. Percent loss estimates are based on USGS feed analyses and the

VSL-CUA Method 5 data given in WHC-SD-WM-VI-027, Table 5.7e (Eaton 1995b). Where the loss of a component was less than or equal to the Sr loss, a value of ~0 is given.

A selective loss value of -27% for P_2O_5 was obtained based on tie component calculations. By examining the data for the P_2O_5 in the glass, it is apparent that the glass concentration, and to a lesser extent the feed concentration, is dropping over time. The ratio of P_2O_5 to SiO_2 calculated for sequential glass sampling times is 7.1, 7.0, 6.6, 6.7, and 5.8 (all x 10^{-3}); the sequential P_2O_5 to SiO_2 ratios in the feed were 4.93, 4.82, and 3.81 (all x 0^{-3}). It is possible that there was phosphorus contamination in the system, and because the glass P_2O_5 to SiO_2 ratio was lagging the feed concentration, the data indicate a volatility gain across the melter with time. Because there are no Method 5 data on which to base an alternate P_2O_5 volatility estimate, it does not appear that there is sufficient information on which to base a defensible estimate.

A special estimate for SO_3 volatility was prepared based on an average of the USGS sample analysis data providing information on SO_3 (three feed, two glass) and using SiO_2 as a tie component. The result indicates SO_3 volatility of 7.2% with sample standard deviation of ±17.3% based on analysis of the USGS sample variability. Analytical data consistently indicate that feed contained more S than the feed target composition. The offgas SO_2 data at the HEPA filter exit are inconsistent with feed data and indicate substantially more SO_2 in the offgas than was fed to the melter.

The 82% volatility result for iodine was determined based on neutron activation analysis of three feed samples and two glass samples using an SiO_2 tie component calculation.

6.3.6 Envitco

The Envitco dry feed test had the lowest selective component volatility losses of any test. Results were determined based on an average of the results obtained using SiO_2, SrO, and Al_2O_3 tie components. With the exception of S and I, losses were too low to accurately determine the volatility using the tie component calculation. However, the results of the tie component calculation confirm that the volatile losses were low. Results obtained based on Method 29 sample data assume that the gross entrainment was 0.05% and have been corrected to account for entrainment. The volatile loss calculations for Cl and F were hindered by poor detection limits on the samples and are given as ranges.

The SO_3 selective loss value of 53% was based on only one glass sample for which detectable SO_3 was reported. Offgas SO_2 monitoring, which indicated SO_2 emissions accounted for 37% of the feed S content, also indicated significant S volatility.

The iodine result of 10% volatility was determined using neutron activation analysis data for one feed sample and three glass samples. The feed sample appeared to be slightly deficient in iodine and if the target feed composition is used, the volatility is calculated at 16% with a maximum

individual result of 24%. However, regardless of the treatment of the data the qualitative conclusion remains that the melter retained a significant fraction of the iodine within the glass.

6.4 TOTAL PARTITIONING TO OFFGAS

Total partitioning of volatile components to the offgas system obtained by combining the non-selective losses (assumed to be entrainment) in Table 6-1 with the selective losses (assumed to be volatility) in Table 6-2, using the methodology described in Section 6.1, are provided in Table 6-3.

Table 6-3. Percent of Feed Components Lost to Offgas for Evaluated Melter Systems.

Component	B&W	WSTC	USBM WHC1	USBM WHC2	USBM WHC3	Vectra	Duratek	Envitco
B_2O_3	70	24	52	24	19	15	0.6	0.2
Cl	88	88	82	N/A	97	64	48	1 to 13
Cs_2O	85	84	63	N/A	40	41	14	0.6
F*	93	91	91	N/A	99.7	16	53	0.90
I	95	98	95	N/A	N/A	83	82	10
K_2O	55	49	36	SE	26	16	0.6	0.05
Li_2O	N/A	5.4	N/A	N/A	N/A	N/A	N/A	N/A
MoO_3	64	26	48	51	46	SE	0.8	0.05
Na_2O	41	17	22	21	7.6	13.5	0.6	0.05
P	46	45	42	SE	55	1.7	SE	0.05
S	55	36	88	SE	94	85	SE	53

*Analytical difficulties experienced with fluoride analysis make all values approximate.

B&W = Babcock & Wilcox
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
N/A = Not available; no analytical information available on which to base estimates.
SE = Source error; no result can be determined because of a significant non-waste simulant source of the component.
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.
WHC = Westinghouse Hanford Company
WSTC = Westinghouse Science and Technology Center

6.5 NO_x EMISSIONS

The generation of NO_x was examined for each of the vendor technologies. An NO_x yield was calculated by comparing the molar feed rate of NO_3^- and NO_2^- to the molar emission rate of NO_x in the offgas. No attempt was made to separate NO_x sources between thermal NO_x resulting from N_2 in air and NO_x resulting from feed N. A 100% yield was assumed to result in 1 mol of NO_x for each mole of NO_3^- and NO_2^- in the feed to the melter. Where appropriate, NO_x yields were calculated separately for the feed preparation processes and for the actual melter unit itself. A summary of the NO_x yields considering the melter unit only is provided in Table 6-4 followed by a brief description of the calculation used to arrive at the value for each vendor.

The NO_x yields during preparation of the USBM Type B feed and Vectra fluid bed calcined feed are given in Table 6-5. The USBM data are from a sample of damp USBM Type B feed taken from the ribbon blender during feed production and tested by PNNL to measure the gases released during the drying and reaction process. The Vectra calcination offgas data were measured during feed calcination by Procedyne and reported in WHC-SD-WM-VI-031, Part 1 (Stegen 1996).

6.5.1 B&W

The NO_x yield of 68% for B&W applies to operation without feed additives to reduce NO_3^-/NO_2^- in the feed and with neither reburn or selective non-catalytic reduction operating. The relatively high yield may be due in part to a relatively high offgas flow rate and generation of thermal NO_x. A substantial fraction of the NO_x measured may be thermal NO_x and not originate from feed N.

Table 6-4. Percent Yield NO_x Based on Melter Feed Nitrate and Nitrite Concentrations.

B&W	WSTC	USBM WHC1	USBM WHC2	USBM WHC3	Vectra	Duratek	Envitco
68	~8	0.03*	N/A	N/A	2.6	13	~33

*Prereacted feed. Does not include NO_x generation in feed preparation. Values including the feed preparation process emissions are USBM WHC1 = 7.4%, Envitco = 25% to 50%.

B&W = Babcock & Wilcox
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
N/A = Not available
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.
WHC = Westinghouse Hanford Company
WSTC = Westinghouse Science and Technology Center

Table 6-5. Offgas for U.S. Bureau of Mines Type B Feed Reaction and Vectra Feed Calcination.

Gaseous species	U.S. Bureau of Mines Type B feed laboratory data		Vectra Technologies, Inc. fluid bed calcination
	mmol release	% of gaseous N released as	% of gaseous N released as
NO_x	23	9.6	3.7
N_2O	18.8	15.6	4.7
NH_3	23.5	9.8	0.4
N_2	78.2	65	91

6.5.2 WSTC

Additives were not used to reduce NO_3^-/NO_2^- in the WSTC feed. The NO_x yield for the WSTC plasma torch was calculated as 8% based on online monitor data. The NO_x is attributed to thermal sources and no change in the online reading was observed between feeding and non-feeding operating conditions. Bomb samples indicated NO_x levels 5 to 20 times higher than the online instruments. The average yield would be approximately 62% if the results of bomb samples were used. The results for Ar from the bomb samples were uncertain and WSTC believed that the bomb samples were more likely the incorrect analysis for NO_x. However, there was significant potential to lose some NO_x due to condensation in sample lines and subsequent scrubbing of NO_x. Therefore, a value higher than 8% yield may be justified depending on the use of the data.

6.5.3 USBM

In the USBM feed preparation process, powdered sugar and activated carbon were added to the feed and the mixture was heated to dry the feed and react the nitrates before feeding the melter. The feed preparation process removed 77.5% of the NO_3^-/NO_2^- from the feed. Offgas data were unavailable from the feed preparation process. However, a sample of the unreacted feed was reacted in the laboratory (at PNNL) and the gases evolved were measured and are shown in Table 6-5. It is estimated that of the nitrogen released as gas in the feed preparation reaction, 9.6% of it is released as NO_x.

The calculated efficiency based on the NO_3^-/NO_2^- destruction within the melter itself is extremely high (99.97%). This value is based on the remaining residue of NO_3^-/NO_2^- within the feed and the NO_x data resulting from monitoring the offgas. Thus, the majority of the NO_x was evolved during the feed preparation process while the amount of NO_x generated within the melter was negligible. Looked at as an integrated process, the overall NO_x yield is (9.6%)(0.775) = 7.4%.

Because the majority of the NO_x would be expected to be generated during the feed preparation process, it would be expected that USBM WHC2 and USBM WHC3 would have roughly the same NO_x yield as USBM WHC1. However, additional offgas data were not collected during the WHC2 and WHC3 runs to allow independent NO_x yield estimates to be made for these runs.

6.5.4 Vectra

The Vectra slurry feed test (MT-2) used sucrose as a feed reductant additive. The 2.6% NO_x yield for this test was the lowest yield obtained from any of the combined feed preparation/melter systems. The estimate was based on two offgas sampling periods during slurry feeding operation that were designated Run 1 and Run 2. The feed characterization data were lacking and the results have been adjusted upward to account for a potential NO_3^-/NO_2^- shortage in the feed corresponding to the apparent shortage of Na.

Feed for the Vectra calcined feed test (MT-4) was prepared from LLW simulant with sucrose added which was calcined in a fluid bed calciner at ~500 °C with glass formers. The estimated fate of the N contained in the simulant NO_3^-/NO_2^- is provided in Table 6-5 for the calcination run. The conversion of 3.7% of the feed nitrogen in NO_3^-/NO_2^- to NO_x is fairly consistent with the data observed with slurry feeding of the melter. However, the data appear to have been taken from a sample point downstream from a caustic scrubber which introduces uncertainty that NO_2 may have been scrubbed before measurement. In any case, the reduction in the NO_x emission during calcination was clearly significant. The data indicate more efficient conversion to N_2 than was experienced in the USBM-1 test with much lower ammonia emissions.

6.5.5 Duratek

The Duratek test added urea to the feed and used a slurry feeding approach. The result of the 13% NO_x yield was based on feed analysis and an offgas flow of 90 $stdft^3/min$, the glass production rate of 1,800 kg/day and glass and feed analysis results. The result is reasonably consistent with results obtained by Duratek (Eaton 1995b). The NO_x yield was calculated based only on the feed NO_3^-/NO_2^- and does not include N contained in the urea.

6.5.6 Envitco

The Envitco test approach added activated carbon to the feed slurry before a spray dry operation. The spray dry operation removed 20% to 30% (assumed 25% for calculations) of the NO_3^-/NO_2^- from the feed. However, information is unavailable on what fraction of the NO_3^-/NO_2^- removed was evolved as NO_x. The melter itself evolved 33% of the NO_3^-/NO_2^- remaining in the spray-dried feed as NO_x. When considering the feed preparation and melter as an integrated system, the melter accounts for a yield of 25% based on NO_3^-/NO_2^- in the feed to the spray dry process, which represents the minimum system NO_x yield. An upper bound of 50% NO_x yield is estimated by assuming that all missing NO_3^-/NO_2^- in the spray-dried feed was evolved as NO_x.

6.6 AMMONIA EMISSIONS

Ammonia emissions were not monitored in all offgas runs. The data that are available are summarized below.

6.6.1 USBM

As shown in Table 6-5, the reactions during feed preparation generated 9.8 mol of NH_3 per 100 mol of N released as gas. The feed preparation process destroys 77.5% of the total feed NO_3^-/NO_2^-. Therefore, the NH_3 yield is (9.8)(0.775) = 7.6% based on the total molar feed rate of NO_3^-/NO_2^- fed to the process. The melter itself produces a NH_3 yield of 0.9% based on the NO_3^-/NO_2^- remaining in the melter feed after the feed preparation process. The overall NH_3 yield based on the feed preparation and melter system is 7.6 + (0.9)(0.225) = 7.8%.

6.6.2 Vectra

Vectra did not collect data on NH_3 emissions for slurry feeding. However, data were available for NH_3 emissions for the fluid bed calciner feed preparation run. As shown in Table 6-5, 0.4% of the feed N contained in NO_3^-/NO_2^- was emitted as NH_3 during calcination of the feed slurry.

6.6.3 Duratek

The Duratek NH_3 yield is calculated neglecting the addition of urea to the feed and is based only on the NO_3^-/NO_2^- content of the feed. On this basis, the melter emitted ~8.8% of the molar feed NO_3^-/NO_2^- as NH_3.

6.6.4 Envitco

Data are unavailable from the spray dry process. However, looking only at the melter and using the NO_3^-/NO_2^- content of the dried feed, the NH_3 yield is 4.1%.

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7.0 PROCESS FLOWSHEETS

Each of the seven Phase 1 melter technologies was integrated into the then current *TWRS Process Flowsheet* (Orme 1994) to identify significant system impacts and uncertainties. The process flowsheet studies described in this section were performed during the middle of FY 1995 and have not been updated to incorporate the latest mass balance results discussed in Section 6.0 of this report. Process flow diagrams (PFD) were prepared for each melter and material balances calculated using preliminary mass balance and components split factor values estimated based on Phase 1 test data. The PFDs are provided in Appendix A and the detailed material balances are provided in WHC-SD-WM-ES-354 (Manuel 1995).

The purpose of process flowsheet development in support of the LLW Melter Testing Program is to demonstrate full-scale plant operation in terms of the equipment required, unit operations, and projected material flows. The process flowsheets are intended to identify potential issues at an early stage of development and are not intended to be used for a more comprehensive, detailed design.

7.1 FLOWSHEET DESCRIPTION

The Tri-Party Agreement (Ecology et al. 1994) flowsheet basis uses in-tank pretreatment with enhanced sludge washing as the separations process for liquid defense wastes at the Hanford Site. The purpose of this process is to segregate the waste into high- and low-level radioactive waste fractions, while minimizing the volumes of HLW and geologic repository disposal costs. The alkaline liquid fraction derived from sludge washing is separated to the LLW stream and the remaining insoluble solids (sludge) fraction is sent to HLW immobilization. A further reduction in the radionuclide content of the LLW fraction is accomplished by Cs ion exchange. The ion-exchange effluent stream is concentrated to 10*M* Na in the LLW feed evaporator and routed to LLW feed accumulation tanks. The concentrated Cs stream is returned and combined with the HLW stream.

For consistency among each of the melter technologies, Revision 0 of the *TWRS Process Flowsheet* (Orme 1994) is assumed for a starting basis. In this flowsheet, the vitrified LLW is quenched with water and roll crushed to form cullet, and subsequently blended with sulfur polymer cement for near-surface, onsite disposal in 5,300-m^3 vaults. The portions of the process flowsheet modified for incorporation of alternative LLW vitrification technologies for the current study include the feed preparation process, the melter, and the melter offgas treatment system.

Volatile feed components are scrubbed with nitric acid from the LLW melter offgas and recycled to the LLW feed evaporator where the stream is concentrated to 10*M* Na. The scrubber vent gases undergo catalytic NO_x destruction (99% efficiency), SO_2 recovery, and HEPA filtration before being released to the atmosphere. Off-specification cullet (<1.0% of total LLW glass) is roll crushed and recycled to the melter feed tank(s) as rework.

The flowsheet assumptions for the seven LLW melter alternatives are derived from available technical information from the vendors and WHC cognizant engineers. In many cases, the assumptions are based on rough order of magnitude estimates extrapolated from melter test data. In areas identified to have high degrees of uncertainty in the absence of test data, the most conservative assumption is used as a placeholder.

7.1.1 Tank Waste Inventory

The chemical and radionuclide feed inventory (Guberski 1995) assumed for each of the flowsheets is summarized in Stream 1 in the TWRS Process Flowsheet. The flowsheet models the flow of ~75 feed components in two phases. The blended tank waste and retrieval water enter the pretreatment flowsheet at a maximum concentration of 5*M* Na and 10 wt% solids. This stream represents the ideal, perfectly blended case and is composed of the entire Hanford Site tank waste inventory (177 SSTs and DSTs). The alternative flowsheets use the inventory assumptions from the *TWRS Process Flowsheet*, Revision 0 (Orme 1994). The tank waste inventory should be considered a *work-in-progress* and is subject to change. Revised assumptions with regard to the total tank waste inventory are presented in WHC-SD-WM-TI-613, *TWRS Process Flowsheet*, Revision 1 (Orme 1995).

7.1.2 Separations and LLW Pretreatment

The blended tank waste is processed through enhanced in-tank sludge washing (Orme 1994). The process leaches 85% of the $Al(OH)_3$ and 75% of the $Cr(OH)_3$, and metathesizes 70% of the phosphate from the solids using concentrated NaOH. The caustic wash is followed by additional water washes (dilute NaOH) for increased separations. The decanted supernates and wash waters are collected and processed through Cs ion exchange, removing 99% of the Cs (DF = 100). The ion-exchange effluent is concentrated to 10*M* Na and sent to accumulation tanks for LLW vitrification.

7.1.3 LLW Vitrification

Section 7.2 contains the specific assumptions used to generate each of the LLW process flowsheets. Material balance calculations are performed using the Aspen Plus Flowsheet Simulation software (Aspen 1988). Refer to Appendix A for the corresponding PFDs.

7.1.4 Volatility and Entrainment

Mass balance measurements from each of the melter tests provided crucial information to support the process flowsheets. The assumptions used are derived from a preliminary evaluation of the Phase 1 testing melter mass balance data. Table 7-1 presents the preliminary volatility and entrainment assumptions for each of the individual melters. These preliminary volatility and entrainment assumptions are, in general, consistent with the later evaluation results presented in Section 6.0 of this report. However, there

Table 7-1. Low-Level Waste Flowsheet Percent Entrainment and Volatility Assumptions. (2 sheets)

Percent	B&W	Envitco	Duratek	PEI	USBM	Vectra	WSTC
Entrainment	10.0%	0.4%	0.4%	0.4%	0.5%	0.4%	0.2%
Volatility	B&W	Envitco	Duratek	PEI	USBM	Vectra	WSTC
Ag+	60.0%	2.0%	20.0%	2.0%	43.0%	2.0%	90.0%
Al+3	0.0%	0.0%	0.0%	0.0%	5.8%	0.0%	0.3%
AM+3	0.0%	0.0%	--	0.0%	--	0.0%	2.0%
As+5	80.0%	10.0%	50.0%	10.0%	38.1%	10.0%	20.0%
B+3	67.0%	1.0%	1.0%	1.0%	50.0%	1.0%	12.1%
Ba+2	0.0%	0.0%	1.0%	0.0%	5.2%	0.0%	0.0%
Be+2	10.0%	0.0%	--	0.0%	--	0.0%	0.0%
Bi+3	70.0%	5.0%	10.0%	5.0%	5.8%	5.0%	10.0%
Ca+2	1.0%	0.0%	0.0%	0.0%	10.6%	0.0%	0.0%
Cd+2	85.0%	2.0%	20.0%	2.0%	88.7%	2.0%	20.0%
Ce+3	0.0%	0.0%	1.0%	0.0%	--	0.0%	0.0%
Cm+3	0.0%	0.0%	--	0.0%	--	0.0%	0.0%
Co+3	0.0%	0.2%	1.0%	0.2%	12.8%	0.2%	0.0%
Cr+3	20.0%	0.1%	10.0%	0.1%	2.6%	0.1%	22.5%
Cs+	88.0%	2.0%	25.0%	2.0%	80.0%	2.0%	50.0%
Cu+2	0.0%	0.1%	1.0%	0.1%	--	0.1%	90.0%
Fe+3	0.0%	0.0%	0.0%	0.0%	--	0.0%	0.5%
Hg+2	100.0%	80.0%	80.0%	80.0%	50.0%	80.0%	99.0%
K+	39.0%	0.5%	1.0%	0.5%	42.0%	0.5%	37.0%
La+3	0.0%	0.0%	1.0%	0.0%	--	0.0%	0.0%
Li+	10.0%	0.0%	1.0%	0.0%	17.6%	0.0%	1.2%
Mg+2	1.0%	0.0%	1.0%	0.0%	4.9%	0.0%	0.2%
Mn+4	0.0%	0.0%	2.0%	0.0%	4.4%	0.0%	1.9%
Mo+6	44.0%	1.0%	2.0%	1.0%	50.0%	1.0%	18.8%
Na+	28.0%	0.2%	0.6%	0.2%	28.0%	0.2%	12.4%
Nb+5	0.0%	0.0%	1.0%	0.0%	--	0.0%	1.0%
Nd+3	0.0%	0.0%	1.0%	0.0%	--	0.0%	0.0%
Ni+3	0.0%	0.1%	1.0%	0.1%	2.9%	0.1%	1.9%
Np+4	0.0%	0.0%	--	0.0%	--	0.0%	20.0%
Pb+4	70.0%	2.0%	20.0%	2.0%	94.8%	2.0%	15.0%
Pd+2	0.0%	0.0%	--	0.0%	--	0.0%	2.0%
Pu+4	0.0%	0.0%	--	0.0%	--	0.0%	2.0%
Rb+	80.0%	1.0%	1.0%	1.0%	--	1.0%	40.0%
Re+7	80.0%	10.0%	--	10.0%	25.0%	10.0%	80.0%
Rh+3	80.0%	0.0%	--	0.0%	--	0.0%	0.0%
Ru+3	80.0%	5.0%	30.0%	5.0%	--	5.0%	10.0%
Sb+5	10.0%	2.0%	10.0%	2.0%	87.5%	2.0%	15.0%
Se+6	90.0%	25.0%	90.0%	25.0%	8.6%	25.0%	50.0%
Si+4	0.0%	0.0%	0.0%	0.0%	2.0%	0.0%	0.0%
Sm+3	0.0%	0.0%	--	0.0%	--	0.0%	0.0%

Table 7-1. Low-Level Waste Flowsheet Percent Entrainment and Volatility Assumptions. (2 sheets)

Percent	B&W	Envitco	Duratek	PEI	USBM	Vectra	WSTC
Entrainment	10.0%	0.4%	0.4%	0.4%	0.5%	0.4%	0.2%
Volatility	B&W	Envitco	Duratek	PEI	USBM	Vectra	WSTC
Sn+4	0.0%	1.0%	10.0%	1.0%	70.0%	1.0%	10.0%
Sr+2	10.0%	0.0%	1.0%	0.0%	5.4%	0.0%	1.0%
Te+6	90.0%	10.0%	50.0%	10.0%	90.0%	10.0%	70.0%
Th+4	0.0%	0.0%	--	0.0%	--	0.0%	0.0%
Ti+4	0.0%	0.0%	0.0%	0.0%	6.6%	0.0%	0.0%
Tl+3	0.0%	1.0%	10.0%	1.0%	5.0%	1.0%	50.0%
UO2+2	0.0%	0.0%	--	0.0%	5.3%	0.0%	10.0%
V+5	0.0%	1.0%	--	1.0%	--	1.0%	5.0%
W+6	0.0%	0.0%	--	0.0%	--	0.0%	0.0%
Zn+2	50.0%	1.0%	20.0%	1.0%	96.0%	1.0%	10.0%
Zr+4	0.0%	0.0%	0.0%	0.0%	--	0.0%	0.0%
Cl-	88.0%	10.0%	60.0%	10.0%	80.0%	10.0%	80.5%
F-	50.0%	10.0%	50.0%	10.0%	50.0%	10.0%	38.6%
I-	100.0%	50.0%	100.0%	50.0%	99.0%	50.0%	80.0%
P	10.0%	1.0%	75.0%	1.0%	50.0%	1.0%	1.5%
S	60.0%	25.0%	10.0%	25.0%	41.9%	25.0%	50.5%
Tc	80.0%	10.0%	50.0%	10.0%	25.0%	10.0%	80.0%
TOC	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
N_2O	--	0.05*	--	0.05*	0.05*	0.05*	--
NOx	1.0*	0.4*	0.2*	0.4*	0.1*	0.4*	0.006*

*NOx/(feed nitrates).

B&W = Babcock & Wilcox
Envitco = Envitco, Inc.
Duratek = GTS Duratek, Inc.
PEI = Penberthy Electromelt International, Inc.
USBM = U.S. Bureau of Mines
TOC = Total organic carbon
Vectra = Vectra Technologies, Inc.
WSTC = Westinghouse Science and Technology Center

are some significant differences. For example, the later mass balance evaluation indicated significantly greater processing losses during the Vectra test than did the preliminary evaluation results presented in Table 7-1.

7.2 VENDOR EQUIPMENT AND PROCESS DESCRIPTIONS

Equipment and process details unique to each of the Phase 1 melter alternatives are described in the following subsections. Equipment numbers are based on the number of melter lines for a 200 tonne/day plant. The Phase 1 target glass composition selected by each vendor and described in Section 5.0 (Table 5-2) of this report is assumed to be processed in the respective alternative melter flowsheets. Two flowsheet alternatives, dry

feed and slurry feed, were modeled and material balances calculated for Envitco. Process flow diagrams were also developed for both the calcined feed and slurry alternatives for Vectra. However, material balances were only calculated for the Vectra slurry feed case.

7.2.1 B&W

Feed Preparation (Slurry)

Equipment
- Four dry ingredient storage bins with weigh feeders
- Four melter feed/mixing tanks
- Four Moyno progressive cavity pumps.

The glass-former mixture consists of $Al_2O_3 \cdot 3H_2O$, boric acid, limestone, and a ratio of microsilica and fine sand (~30:70). For simplicity, the microsilica and fine sand are labeled as SiO_2 in the material balances. The boric acid (dry) is assumed to react with the NaOH waste in the melter feed tank by the following reaction:

$$H_3BO_3 + NaOH \rightarrow NaBO_2 + 2H_2O$$

Melter

Equipment
- Two cyclone combustion melters and glass reservoirs.

Fuel (kerosene) is added to the combustion furnace at a rate of 0.84 kg/kg wet feed. A fresh supply of oxygen (~95% O_2, 5% N_2) is mixed with the recycled flue gas to achieve a 3% O_2 excess in the melter offgas. The flue gas recycle split fraction is varied to achieve a stream concentration of 25% O_2 to serve as combustion air to the melter. Atomizer air is supplied at a rate of 1.43 kg/kg feed.

The reactions assumed for the B&W melter include 100% conversion of feed nitrates to NO_x, where the NO_x is 90% NO and 10% NO_2. Phase 1 test NO_x yield values indicate <100% conversion; however, 100% was used for this study. The flowsheet assumes 10% solids entrainment and 28% Na volatility. Scoping tests have demonstrated lower entrainment values; if this is conclusive, the entrainment assumption may decrease from 10% in the next iteration of the flowsheet calculations.

Offgas System

Equipment
- IFGT
  - Four heat exchangers
  - Two gas mixing stations
  - Two flue gas recirculation fans
  - Two IFGTs (integrated condenser/scrubber)
  - Two demisters
  - Two scrub solution staging tanks.

The design of the B&W melter offgas treatment system differs from the LLW offgas system modeled in the *TWRS Process Flowsheet* (Orme 1994). The melter offgas is cooled to 149 °C and is sent to the IFGT where 90% of the particulate is captured and recycled to the LLW feed evaporator. The humidity above the IFGT (based on technical information provided by the vendor) is specified as 6 wt% H_2O. The demister attains a 98% particulate removal efficiency, and its vent gases produce the flue gas recycle stream, a fraction of which is mixed with fresh oxygen and recycled to the melter, as previously described.

7.2.2 Envitco

Feed Preparation (Type A - Dry, Reacted Feed)

Equipment
- Four dry ingredient storage bins with weigh feeders
- One pug mill
- One extruder/pelletizer
- One infrared belt dryer
- Four dry batch surge bins with weigh feeders
- Four X-Y spreaders (i.e., one per melter).

The dry glass formers are preblended in a ribbon blender and include hydrated alumina, boric acid, and a ratio of microsilica and fine sand. The stoichiometric amount of a carbon reductant is also preblended with the glass-former mixture. For simplicity, the ideal reactions are assumed:

$$3C + 2NO_3^- \rightarrow 3CO_2 + N_2$$
$$2C + 2NO_2^- \rightarrow 2CO_2 + N_2$$

In the actual plant operation, some NO_x will be produced from other reductant reaction mechanisms. The complete data for the non-ideal reactions were not available for the Envitco flowsheets. For the Type A feed, reactions with the carbon reductant are assumed to take place in the infrared belt dryer. Feed Type B assumes that the ideal reactions occur in the melter. In the belt dryer, all the water is removed from the LLW feed pellets, and the reaction conversion of feed nitrates to CO_2 and N_2 is set to achieve the following melter offgas NO_x to feed NO_3^- ratio specifications:

NO_x/(feed nitrates) = 0.4 (0.3 from Phase 1 test data)
N_2O/(feed nitrates) = 0.05.

Feed Preparation (Type B - Slurry)

Equipment
- Four dry ingredient storage bins with weigh feeders
- Four melter feed tanks
- Four slurry pumps
- Four X-Y spreaders (one per melter).

Dry glass formers and reductant are added in the same manner as described for the Type A feed. Reactions are similar to those in the Type A dry feed, but occur in the melter rather than in the belt dryer.

Melter

Equipment
Four Joule-heated, cold-top melters with six top-loading molybdenum electrodes per melter.

The Envitco melter design uses an overflow side drain for normal glass pouring. The melter also includes the capability to remove salts from the melt surface via salt taps, and the capability to remove metals and sludge from the melter via a bottom drain, to prevent accumulation in the melter. For the flowsheet, a flow of zero is assumed for the salt taps and bottom drain. No provision for the handling of these potential secondary waste streams is depicted in the flowsheets. It is assumed that sufficient control over the formation of salts and metals is feasible through careful blending and retrieval sequencing. Further studies are necessary to determine the probability of salts and metals formation in all the Joule-heated melters.

A 0.4% entrainment and a 0.2% Na volatility are assumed based on conservative estimates extrapolated from Phase 1 mass balance data.

Emergency Seal Pot

A feature illustrated in the Envitco feed Type B melter is the emergency seal pot system. It is recommended that this system be integrated into all the slurry feed or moist feed Joule-heated melter systems, including Envitco Type B, Duratek, PEI, and Vectra. The purpose of this system is to vent the gases in the event of a pressurization of the melter's contents and subsequent rupture of the cold top. In such an event, the gases evolved would be released into the atmosphere. For the flowsheet, zero flow is assumed. This emergency system is another area that requires further investigation.

Integrated Offgas Systems (Feed Preparation and Melter)

For the Envitco Type A feed, the melter offgas is combined with the dryer offgas and cooled in the offgas quench tower(s). The practicality of combining the offgas streams should be examined in more detailed design studies. The addition of an uncoupled offgas system for the feed preparation system will significantly increase the complexity of the Type A flowsheet, as well as for other dry feed flowsheets. A combined offgas system requires much tighter control, and therefore may be operationally impractical. In this analysis, however, a second offgas system for the dryer was omitted from the flowsheet to prevent the choice of an offgas system from becoming a *major* discriminator in the selection of a vitrification technology.

Offgas System (TWRS Reference Flowsheet)

Equipment
Four quench towers (one per melter)
Four venturi scrubbers (one per melter)
Four demisters (one per melter).

Except for the number of parallel equipment lines (one per melter), the assumptions for the Envitco melter offgas system are consistent with those described in the *TWRS Process Flowsheet* (Orme 1994). The melter offgas system assumptions for the flowsheets are as follows:

95% particulate removal efficiency for the quench tower(s)
95% particulate removal efficiency in the venturi scrubber(s)
98% particulate removal efficiency in the demister.

The spent scrub solution is recycled to the LLW feed evaporator, and the demister vent gases are processed for atmospheric release.

7.2.3 Duratek

Feed Preparation (Slurry)

Equipment
Three feed adjustment tanks (one per melter)
Three dry ingredient storage bins with weigh feeders
Three melter feed tanks
Three slurry pumps.

Dry, preblended glass formers are added to the melter feed tanks to achieve a target waste oxide loading of 25 wt%. This specification is slightly different from the manner in which the glass formulations are given in the other melter alternatives.

Dry urea, $(NH_2)_2CO$, is added to the melter feed tank(s) primarily to control NO_x emissions. The flowsheet assumes that urea is added at a rate of 250 g/L feed (LLW + glass formers). The conversion of nitrates by ideal reactions with urea is set to 0.2. The urea reactions assumed to take place in the melter are as follows:

- $(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2$
- $2NO_2^- + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$

The urea reactions may proceed through other mechanisms; however, the ideal reactions are assumed. Control of excess ammonia emissions also warrants further consideration.

Melter

Equipment
Three Joule-heated, cold-top melters, each with four fixed-plate electrodes.

The proposed Duratek melter design operates with a bubbler to enhance the convective flow in the molten glass. In the flowsheet model, the bubbler air flow rate is scaled up from the Phase 1 test melter to 2,000 $stdft^3/min$ for all three melters (667 $stdft^3/min$ air/melter). An important impact to be considered is that the use of bubbler air increases the offgas flow rate, which may require additional quench water for cooling. This sensitivity will affect the design of the offgas equipment.

The entrainment for the Duratek melter is specified as 0.4% and the Na volatility is 0.6%. The melter offgas NO_x specifications are as follows:

- NO_x/(feed nitrates) = 0.2 (0.11 during Phase 1)
- N_2O/(feed nitrates) = data unavailable.

The Duratek melter uses an airlift side drain for normal glass pouring, but is assumed to have a bottom drain to prevent accumulation of sludge in the melter. As in the Envitco, PEI, and USBM melters, a flow of zero is assumed for the bottom drain, and no provision for the handling of these potential secondary waste streams is shown in the PFD.

Offgas System

Equipment
Three offgas quench towers
Three venturi scrubbers
Three demisters.

The offgas system assumptions for the Duratek melter are identical to those of the Envitco melter previously discussed.

7.2.4 PEI

Phase 1 melter test data are unavailable for the PEI melter alternative. Therefore, because of the similarities in their designs, the same melter volatility, entrainment, and NO_x generation assumptions are used for the Envitco and PEI vitrification technologies.

Feed Preparation - Slurry/Absorbent Glass Formers

Equipment
Four dry ingredient storage bins with weigh feeders
Four screw chargers (number per melter to be determined).

This feed preparation option is unique among the process alternatives because it requires the least amount of equipment. Absorbent glass formers, which comprise ~70% of the total glass-former mass, are fed in order to reach the target glass formulation. Absorbent glass formers in the LLW melter feed allow the mixture with the liquid LLW to be accomplished in-line at the feed point to the screw charger. The resulting blend is auger-fed into the melter feed port(s), eliminating the need for slurry pumps. The glass formers used in this melter process alternative are sand (SiO_2), limestone (CaO), and floor dry (SiO_2, Al_2O_3).

Melter

Equipment
Four Joule-heated, cold-top melters with multiple (number to be determined) sidewall molybdenum electrodes.

The PEI melter is assumed to have an overflow side drain for normal glass pouring and have a bottom drain to prevent accumulation of sludge in the melter. As in the Envitco, Duratek, and USBM melters, a flow of zero is assumed for the bottom drain, and no provision for the handling of these potential secondary waste streams is shown in the PFD.

Offgas System

The offgas treatment system is identical to the Envitco Type B flowsheet.

7.2.5 USBM

Feed Preparation (Dry, Reacted Feed)

Equipment
- Two dry ingredient storage bins with weigh feeders
- Three ribbon blenders
- Three ring pelletizers
- One tunnel kiln
- Two dry batch surge bins with weigh feeders.

The dry, reacted feed preparation system for the USBM melter closely resembles the Type A feed for the Envitco melter. Envitco borrows its design from the USBM dry feed concept.

The dry glass formers added are hydrated alumina, boric acid, limestone, microsilica, and fine sand. Testing was performed with sugar and carbon reductants, and a ratio of the two reductants may be recommended as the result of further testing. For ease of illustration, the flowsheet assumes only carbon is used.

Melter

Equipment
- Two carbon electrode melters with three top-fed electrodes per melter.

In the flowsheet, the flow of purge air to the electrodes is set to zero. The ratio of melter NO_x to feed nitrates (NO_x/feed nitrates) is 0.1 (0.09 is calculated from Phase 1 tests). The 5.0% entrainment and a 28% Na volatility are assumed based on preliminary mass balance data.

The USBM melter is assumed to have side drains for normal glass pouring and have a bottom drain to prevent accumulation of sludge in the melter. As in the Envitco, Duratek, and PEI melters, a flow of zero is assumed for the bottom drain, and no provision for the handling of these potential secondary waste streams is shown in the PFD. However, because of the reducing conditions present in the carbon electrode melter, accumulation of precipitated metals and sludge at the melter bottom may require more frequent use of the bottom drain than with the three Joule-heated melters.

Offgas System

The offgas treatment system for the USBM melter is identical to that of the TWRS Process Flowsheet and is described in the assumptions for Envitco.

7.2.6 Vectra

Feed Preparation

Equipment
Four dry ingredient storage bins with weigh feeders
Four melter feed tanks
Four slurry pumps.

The slurry feed system for the Vectra melter is identical to that of the Envitco Type B (slurry) feed. A PFD of the calcined feed process tested by Vectra during Phase 1 is also included along with the slurry feed PFD for reference in Appendix A.

The glass formers used to meet the target glass composition are Al_2O_3, B_2O_3, $CaCO_3$, $MgCO_3$, Fe_2O_3, and SiO_2. The $CaCO_3$ and $MgCO_3$ may be batched primarily as powdered dolomite. A stoichiometric amount of sugar is added as a reductant to the melter feed tank. The sugar is preblended with the dry glass formers. The flowsheet integrates the ideal reactions, although non-ideal reactions (evolving NO_x and N_2 in the melter offgas) are assumed to occur.

Melter

Equipment
Four Joule-heated, cold-top melters with six top-fed molybdenum electrodes per melter.

The Phase 1 melter test data collected by Vectra indicate a need for a possible six melters for this melter alternative. The PFDs show four melters, whereas the facility layouts and cost estimate studies performed to support this project are based on six melters.

Electrode purge gas is set to zero for the flowsheet. The ratio of NO_x to feed nitrates is set to 0.4, which is consistent with the calculations in the Phase 1 test data. The ratio of N_2O to feed nitrates is 0.05. The entrainment is 0.4% and the Na volatility is 0.2%.

Offgas System

The offgas system chosen for the Vectra melter alternative is identical to that used in the TWRS Process Flowsheet.

7.2.7 WSTC

Feed Preparation (Slurry)

Equipment
Forty dry ingredient storage bins with weigh feeders
Forty Moyno progressive cavity pumps.

Ten torches connected to each of four melters are fed by individual feed systems. The Moyno pumps and feeders exist outside the melter cell. The LLW and glass formers are blended in-line at mix points before each torch.

Glass formers are slurried with water to 80 wt% solids at the exit of the Moyno pump. The LLW evaporator duty is increased to attain a 15*M* Na concentration (37.5 wt% H_2O) in the evaporator bottoms so that upon mixture with the slurried glass formers, the melter feed stream is 10*M* Na. The glass-former composition is adjusted to meet the target glass formulation. A non-borosilicate glass is recommended in order to overcome the high volatility of sodium borate compounds. Volatility assumptions are based on Phase 1 tests with a non-borosilicate glass.

Melter

Equipment
Four plasma carbon electrode melters with ten plasma torches each.

The supply of torch air is adjusted to 112 m^3/min. To minimize thermal NO_x, the flow of shroud air is set to zero. The NO_x destruction specifications assumed are as follows:

NO_x/(feed nitrates) = 0.006 (0.08 from Phase 1 calculations)
N_2O/(feed nitrates) = data unavailable.

The entrainment and Na volatility assumptions are 0.2% and 12.4%, respectively.

Offgas System

The offgas system chosen for the WSTC melter alternative is identical to that used in the TWRS Process Flowsheet.

7.3 LLW PFDs AND MATERIAL BALANCES

Process flow diagrams for each of the melter alternatives are presented in Appendix A. The PFDs illustrate the unit operations and stream and equipment identifications used for the flowsheets. Equipment identifications are consistent with the facility layouts.

The material balance tables for each melter alternative are provided in Appendix A of WHC-SD-WM-ES-354 (Manuel 1995). The streams reported in these tables are presented on a component basis in two phases: liquid and solid. The liquid phase represents all the soluble components and/or gaseous phase components (i.e., melter offgas components appear in the 'LIQUID COMPONENTS'

table). The solid phase represents components that are insoluble or present as glass oxides. The values shown in the material balances are reported as total flows in tonnes. This represents the steady-state, cumulative amount of each component to be processed during the entire tank waste treatment campaign. A rate basis can be calculated by assuming a number of operating days and a total operating efficiency.

7.4 DISCUSSION AND RECOMMENDATIONS

At this stage of development, and coupled with the uncertainties of the process flowsheets, no significant issues were ascertained from the process flowsheets. As previously discussed, the results of this study are preliminary in nature. Because of limited data resources, it is difficult to determine whether a flowsheet issue should be considered critical or merely a function of the uncertainties involved. A more in-depth analysis of the results of this study must be accompanied by a traceable record of all assumptions integrated into the calculations, as well as some provision for consistency among the alternative melter technologies.

Examples of some of the criteria from which the flowsheet operations can be judged are simplicity of the process, volatility, number of parallel processes, number of offgas systems, sensitivity to design parameters, and purge streams.

- Simplicity of the process--A more complex process leads to greater uncertainty in the flowsheet and the ability to predict the behavior of the full-scale process. Therefore, more complicated designs require more development and engineering.

- Volatility--The flowsheet assumes that losses to the melter offgas are controlled by recycle. Therefore, high volatility can lead to difficulty in handling large concentrations of components in the recycle streams and buildup of these components if their solubilities in the glass are exceeded. High volatility and the resulting large recycle stream also complicate process and product composition control. High Cl and F losses can be troublesome should they accumulate to large proportions because of their corrosive effects on offgas handling equipment. In addition, Cl has a low solubility (~1%) and is therefore difficult to recycle. Volatile components that cannot be effectively recycled require secondary streams, requiring additional treatment processes.

- Number of parallel processes--While the impacts of the number of parallel processes are not directly represented in the flowsheets, the design, maintenance costs, and operational complexity are concerns.

- Number of offgas systems--Vitrification processes that require a feed preparation system to dry and react the feed before its introduction into the melter will likely require a separate uncoupled offgas system for the feed processing equipment.

- Sensitivity of design parameters--The plant design must include the capability to deal with upsets, the potential and frequency of which must be carefully anticipated in thorough design studies.

- Purge streams--Secondary streams must be minimized or eliminated. Purging undesired byproducts through secondary streams is acceptable only if a treatment process exists.

Continued refinement of the flowsheet is necessary in order to identify the discriminating issues in melter comparison studies. The methods used to derive the assumptions should be standardized to ensure consistency. With limited test data, the resolution of certain issues cannot be accomplished. For example, inaccuracies in the volatility assumptions may translate into inaccuracies in equipment sizing, materials specification, and cost. A logical step toward resolving these issues would be to perform a series of parametric analyses to better identify the key data needs.

8.0 FACILITY CONFIGURATION STUDY

To evaluate the impact of different melter technologies on a 200 tonne/day vitrification plant at the Hanford Site, Fluor developed preliminary facility configuration layouts for each technology and completed a cost comparison based on these layouts. Because only Phase 1 of the melter testing program had been completed and no extensive operations testing or testing of remote capabilities was included, a more detailed design study could not be performed. In the absence of detailed information on how each technology would be designed into a remotely operated vitrification facility, Fluor used technical information from the melter vendors and advice and information from the WHC cognizant engineers to modify a general radioactive facility concept to accommodate each technology. Where information was lacking, Fluor and WHC made estimates so that the preliminary facility layouts could be completed.

The primary objective of this section is to provide examples of how each melter technology may be incorporated into a radioactive LLW vitrification facility via the preliminary facility drawings provided in Appendix B. Discussion of design details and issues, or design alternatives, is beyond the current scope. It also should be noted that these facility configuration concepts share many common features and are not optimized for the particular melter and feed system technologies.

8.1 COMMON ASSUMPTIONS AND CONSIDERATIONS

Glass-former feed systems are generally located in 'no-maintenance' areas above the melter cell. When possible, feed systems using slurries are located in modular cells to facilitate maintenance activities. Feed system layouts are in the 'detached plan x' in facility plan views in Appendix B.

The melter envelope includes a metal frame where all piping and electrical jumper connections are interfaced with the melter. The melter cell layouts allow 2 to 3 m between the melter cell walls and the melter frame to allow for jumper connections. The melter support frames are mounted on rails to permit moving melters from melter staging areas and/or melter cutup cells. In most cases, the melter offgas system was included in the melter cell. Maintenance in the melter cell is provided by a bridge crane. An electro-mechanical manipulator may be attached to provide for more dexterous handling operations.

The offgas systems for all technologies, except for B&W, were considered to be generic in the equipment components used, but were scaled to size based on the mass flow rate into each equipment component. The system for handling the molten glass product also was generalized to the 1994-95 *TWRS Process Flowsheet* (Orme 1994) in which the glass is processed into cullet and mixed with a sulfur polymer cement matrix. Process flow diagrams and identification of equipment components summarized in Section 7.0 and Appendix A of this report were assumed for each melter technology. Mass flow rates assumed for equipment sizing are reported in WHC-SD-WM-ES-354 (Manual 1995).

Other features such as catch tank areas, remote cutup and decontamination cells, melter cutup cells, and flasking* areas, considered to be necessary in a radioactive vitrification facility, were included in the layouts. In some cases, these common features were scaled to meet the needs of the technology, and in others, the features were common to all technologies.

Appendix B contains drawings of facility layouts developed by Fluor for each of the six technologies. Plan views and several vertical sections of the vitrification plant were included for the Envitco layout to show the various areas of the plant. For the rest of the technologies, only a plan view and one vertical section through the melt cell were included to highlight the differences among the layouts.

The model for this study was WHC-SD-WM-ES-295, *Tank Waste Remediation System Facility Configuration Study* (Boomer 1994), a more detailed project that evaluated several types of vitrification activities.

8.2 DISCUSSION OF FACILITY LAYOUTS

Selected process options and assumptions used for each technology are summarized in the following subsections. Facility layout drawings developed for each melter system are contained in Appendix B. Several of the vertical section views of the facility layout developed for the slurry-fed Envitco melter are common to other melter technologies and are therefore only provided for the Envitco melter.

8.2.1 Envitco

The Envitco layout included four 50 tonne/day melters to reach the 200 tonne/day plant capacity. Two layouts were completed for Envitco because it was unclear at the time of this study which type of feed system would be more desirable. One layout was done with a dry feed system using the USBM Type B feed preparation system as a basis. It was believed that using dry feed would significantly increase the glass processing rate over a comparable slurry feed; however, results from Phase 1 testing indicated that this may not be the case. The other Envitco layout was done for a wet or slurry feed. The significant difference between the two layouts is that a large feed drying furnace is needed for the dry feed system. Eliminating the drying furnace made it possible to use only two melt cells, each containing two melters, instead of the four melt cells used in the dry feed layout.

Several drawings of the plant layout for the Envitco technology are included in Appendix B. The first series of drawings, Figures B-1 through B-7, show the plant design for the Envitco technology using a slurry feed system. Figure B-1 is a plan view at the melter cell floor level. This figure indicates the location of the vertical sections in Figures B-3 through B-7. Figure B-2 is a plan view at floor level of the flasking area which also

*Flasking is a remote maintenance system in which equipment is transferred through cell ports via 'flasks' (casks) for maintenance or replacement.

shows the location of vertical sections. Figure B-8 is a plan view of the facility layout developed for the Envitco melter using dry feed prepared by the USBM Type B feed process.

8.2.2 Vectra

The Vectra facility layout included six 33 tonne/day melters and used a slurry feed system. In this configuration, two of the melters were contained in individual melt cells while the remaining melters were grouped two to a cell. During the facility configuration study, Vectra was considering proposing melters in the 25 to 50 tonne/day capacity range; a 33 tonne/day design was selected for this facility study. Vectra later proposed a 50 tonne/day design and provided preliminary specifications for a 100 tonne/day design. A more optimized layout is possible using four 50 tonne/day or two 100 tonne/day melters.

Figure B-9 shows a plan view of the Vectra layout at the melt cell floor level as well as a detached plan view of the feed preparation area above the melters. The vertical section shown in Figure B-10 for this layout cuts across the plant showing the relative position of the melt cells to other areas of the plant.

8.2.3 PEI

A facility layout was not completed for the PEI technology due to the lack of technical information provided by PEI and incomplete Phase 1 melter test results. This technology also was omitted from the cost comparison.

8.2.4 Duratek

The Duratek layout included three 67 tonne/day melters and used a slurry feed system. As with the Vectra layout, the type of floor plan used in this study lends itself to two or four melters better than three. In this Duratek layout, two of the melters are combined in one melt cell and the other melter is contained in its own melt cell.

Figure B-11 shows a plan view of the Duratek layout at the melt cell floor level as well as a detached plan view of the slurry feed preparation area above the melters. The vertical section down the length of the vitrification plant is shown in Figure B-12.

8.2.5 USBM

The USBM layout included two 100 tonne/day melters to achieve the 200 tonne/day plant processing rate. The layout was designed so that additional sections of carbon electrode could be remotely added. It also had been suggested that 'form in place' electrodes could be used, but a plant layout different from that of the other technologies would have had to be used.

The feed system used for the USBM layout was the Type B dry feed system. Glass-former additives, reductant additives, and liquid LLW are mixed as a wet paste which is extruded as pellets that are then dried and reacted. This system required a large drying furnace that significantly increased the size of the vitrification facility. However, it was determined in later testing by USBM that it may be possible to operate the melter technology using damp or wet feed which would eliminate the need for a large drying furnace.

Figures B-13 and B-14 show a plan view of the USBM layout at the melter cell floor level as well as a detached plan view of the feed preparation and drying area above the melters. In contrast to the Envitco layout, this design shows the feed drying furnace above the melter instead of between the melters at the lower level.

8.2.6 WSTC

The WSTC layout used four 50 tonne/day melters to achieve the 200 tonne/day plant capacity. Each melter had ten plasma torches that could be individually removed and maintained. This modularity lends itself to simplified maintenance if the facility were designed so that the torches were accessible from outside the melt cell, but again, this layout was not optimized for this technology. This layout, as with others, included two melters in each of two melt cells.

The WSTC system used a method of slurry feeding slightly different from that of other technologies. The proposed slurry feed system for this technology was to continuously combine metered liquid LLW streams with metered slurry streams of nonradioactive glass additives or frit and directly inject the combined slurry streams into the melter. The advantage of this type of feed system is to keep as much of the feed processing in the nonradioactive environment as possible.

Figure B-15 shows a plan view of the WSTC facility layout at the melt cell floor level as well as a detached plan view of a tank area above the melters. A vertical section through a melter cell area is shown in Figure B-16.

8.2.7 B&W

The B&W layout included two 100 tonne/per day melters, each with a glass receiving reservoir. The relatively small cyclone combustor could be separated from the reservoir and remotely replaced. This technology used a wet paste feed injected into the melter with compressed air. It was believed that only a small amount of molten glass would be contained in the melter system, so no catch basin was included in this layout.

Figure B-17 shows a plan view of the B&W layout at the melt cell floor level as well as a detached plan view of a tank area above the melters. A vertical section through a melter cell area is shown in Figure B-18.

8.3 SUMMARY AND RESULTS

Facility areas that were significant contributors to the differences in size and cost were the melt cell area, the feed preparation area, and the melter cutup cell area. The melt cell areas were between 480 and 2,468 m^2. The separate feed preparation areas were between 134 and 644 m^2, although in some of the layouts the feed preparation equipment was placed inside the melter cells. The melter cutup cell areas were between 275 and 1,744 m^2.

Although the plant layouts were useful for project engineers and vendors to see how the different technologies might look in a fully remote vitrification facility, the absolute plant volumes as well as the cost values should be viewed with caution because this was only a preliminary study. Estimates of facility cost ranged from $1,732 million to $2,640 million, depending on the technology. The cost estimates included feed preparation systems and melter offgas treatment, but did not include melter costs.

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9.0 SAFETY AND ENVIRONMENTAL

The Phase 1 melter technologies were evaluated based on safety and environmental criteria. The safety evaluation was performed by Fluor for WHC. The environmental evaluation was performed by WHC. Detailed results of these evaluations are documented in WHC-SD-WM-ES-350, *Comparative Low-Level Waste Melter Safety and Environmental Evaluation* (Colby and Leach 1995). The purpose of the study was to identify potential safety and environmental discriminators among the melter technologies.

9.1 SAFETY EVALUATION

The safety evaluation provides a safety and operability assessment of the melter concepts considered in the Phase 1 LLW melter evaluation effort. The findings from the safety study are intended to help determine which melter concepts need further testing and to provide details on specific items that should be investigated.

Melter technology selection will need to consider how the melters will operate in a 200 ton/day plant in a remote environment. This study endeavors to evaluate each melter based on expected final design characteristics. The full-scale extrapolation basis is documented in the 'design intent statements' contained in WHC-SD-WM-ES-350. These design intent statements relate how each melter subcomponent and associated instrumentation is expected to function in a 200 ton/day remote operation. The design intent statements reflect process variables such as flow, pressure, and temperature as well as materials of construction and instrumentation.

9.1.1 Scope

The safety study excluded support systems that were preliminary and can be expected to change significantly during their evolution to final design, including the following:

- Feed preparation system
- Product glass handling system
- Melter offgas system downstream of the ejector venturi scrubber.

Non-normal operating modes were not reviewed in the absence of adequate operating procedures. Operating procedures that discuss step-by-step activities including human-equipment interface, alarms, and protective system checks are essential to a proper review. Therefore, this study focused on the normal operating mode and did not attempt a rigorous evaluation of the following modes:

- Initial installation
- Melter startup
- Melter idle
- Melter restart after upset
- Reduced capacity operation
- Melter shutdown

- Melter decontamination
- Melter removal
- Maintenance activity.

The study investigated the safety and operability of each melter concept using a team approach and a structured hazard and operability methodology. The study specifically reviewed each melter design for the following hazards:

- Potential onsite/offsite impacts
- Potential impacts to in-facility workers
- Potential threats to the processing mission.

9.1.2 Analysis and Conclusions

A safety review team reviewed the melters using a systematic hazard and operability approach as defined in *Guidelines for Hazard Evaluation Procedures* (AICHE 1992). The functions of all melter components were detailed; deviations from the intended normal operating conditions were postulated during safety review team sessions. The causes and consequences of each deviation, as well as protective and mitigating features, were formulated. The review team evaluated the likelihood of the deviation's occurrence and the severity of its effect on safety and operability. A qualitative risk code was then applied for the purpose of ranking. The design intents and full worksheet results for each melter are shown in the appendixes of WHC-SD-WM-ES-350; critical findings are summarized here. The critical findings are classified as either development items or engineering items. Development items will require additional research and testing by the melter vendor to address the issue. Engineering items will require design effort by either the melter vendor or the Architect-Engineer.

9.1.2.1 Common Findings. The review found many concerns common to all melters because they share the same equipment. For example, the melter offgas system is assumed to have a water spray system downstream of the melter as well as an ejector venturi scrubber. The water spray located immediately downstream of the melter cools the offgas sufficiently to allow an Inconel duct to transfer gas to the ejector venturi scrubber. The scrubber removes much of the volatile radionuclides in the melter offgas stream. The critical items are shown in Table 9-1.

All melter evaluations identified a concern for the potential high flow of spray water resulting from a malfunction in the instrumentation or a nozzle fracture. The high water flow could thermally shock and damage the refractory lining near the water spray nozzles. The replacement time is estimated to exceed 10 days. The spray system needs to be sized to physically limit the water flow to a safe maximum.

Cooling water loss to the ejector venturi scrubber potentially allows contaminated gas to flow to the contact-maintained melter offgas areas. The HEPA filter provides protection; however, it should not be the single protective device.

Table 9-1. Common Melter - Findings.

Item	Cause and consequences	Recommendation
Melter offgas		
Spray cooler	Instrumentation malfunction or nozzle wear/failure → thermal shock to melter refractory → duct replacement	Development item: critical sizing of components to ensure cooling water flow stays within prescribed limits under all conditions
Scrubber	Cooling water loss to the scrubber → contaminated gas flows through melter offgas to contact maintained areas → worker exposure	Engineering item: design cooling water system for high reliability
Drain valve		
Induction-heated drain valve	Loss of cooling water during final melter evacuation → inability to shut off glass flow → glass spill and cell contamination	Development item: drain valve sizing is critical Engineering item: design freeze valve cooling water system for high reliability

This review identified considerable concern for the use of an induction-heated bottom drain valve for the final evacuation of glass before replacement. If the valve fails to close because of cooling water loss, the full contents of a melter or reservoir may flow into the cell. Backup cooling water is recommended if an induction-heated valve is used. An additional recommendation is to use a mechanical valve because it has better experience in this application at other vitrification facilities. In the WSTC and B&W melters, the glass volume in the reservoir or crucible is small compared to that of a Joule-heated melter. For these systems, it is recommended that the quench tank be sized to hold the full melter contents.

9.1.2.2 B&W Melter Findings. The B&W cyclone melter findings are summarized in Table 9-2. Most of the concerns identified can be eliminated or mitigated to a safe level with current technology. The burner management system is a safeguard for many of the deviations but its logic has not been developed. The study team combined experience and best judgement to determine the probable burner management response to simple deviations. As the burner management system is being developed, it must undergo exhaustive evaluation to ensure the safety of the plant; however, burner management systems are a common item in many industries and this is not deemed an insurmountable problem.

9.1.2.3 USBM Carbon Electrode Melter Findings. The USBM carbon electrode melter findings are summarized in Table 9-3. Concerns identified will require development work to resolve. Potential reaction between the carbon electrodes and moisture in the feed may result in the production of flammable gases such as CO and CH_4. In addition, accumulation of flammable free carbon (soot) was identified as a concern. The USBM test system used a thermal reactor (after burner) in the offgas system (near the melter exit), which burned flammable gases. The reliability and capability of a thermal reactor will need to be fully tested during development, and associated safety risks carefully

Table 9-2. Babcock & Wilcox Cyclone Melter - Findings.

Item	Cause and consequences	Recommendation
Fuel and oxygen systems		
Kerosene line	Line rupture → possible fire	Engineering item: protective routing; reliable burner management system; shut off waste, fuel, and oxygen on low pressure
	Control system malfunction → control valve opens → accumulation of kerosene in offgas system → fire or explosion potential	Engineering item: provide an O_2 sensor and a reliable burner management system
Oxygen line	Line rupture → possible fire if organics are present	Engineering item: protective routing; reliable O_2 supply sensors; reliable burner management system; shutoff capability
	Control valve fails → low O_2 flow → accumulation of kerosene in offgas system → fire or explosion potential	Engineering item: reliable burner management system
	Loss of melter offgas blowers with potential for fire or explosion	Engineering item: reliable burner management system
Recycle systems		
Recycle line	Mechanical impacts → cell contamination	Engineering item: protective routing of line
Offgas		
Screen tube	Leak from cooling water system → corrosion of economizer	Engineering item: minimize potential corrosion or other causes of leaks Development item: determine necessity of feed tubes and eliminate if possible

Table 9-3. U.S. Bureau of Mines Carbon Electrode Melter - Findings.

Item	Cause and consequences	Recommendation
Melter integrity		
Melter plenum	Flammable gas production and/or carbon buildup → potential explosive conditions if mixed with air or oxidants	Development item: demonstrate a means to destroy potentially explosive particulates and gases
Offgas		
Flammable gases	Reaction between carbon electrodes and water may produce flammable gases → potential explosive conditions if mixed with air or oxidants	Development item: determine flammable gas production potential and develop means to mitigate potentially explosive offgas mixtures
Feed inlet chute	Waste feed inlet chute does not extend into plenum → particulate entrainment in offgas	Development item: determine if proposed pelletized fuel poses particulate problems; if so, develop solution

evaluated. If future testing shows the quantity of fine particulate carbon accumulation is significant, measures must be taken to mitigate its hazard potential.

The inlet waste feed chute does not extend into the melter plenum space. Consequently, there may be a tendency for particulate matter to be entrained in the offgas. This may overload the scrubber and the recycle stream. Future testing should evaluate the quantity of particulates and their impact on the scrubber.

9.1.2.4 Duratek Melter Findings. The Duratek melter findings are summarized in Table 9-4. All the concerns identified can be eliminated or mitigated to a safe level with current technology. A major cold-cap disruption could cause an overpressure that could rupture the melter offgas duct and result in cell contamination. For the melter offgas duct to be designed to accommodate this condition, further testing is needed to identify the worst-case overpressure from a cold-cap disruption. One solution could be the addition of seal pots to the melter offgas system for slurry-fed Joule-heated melters (see Section 7.0).

The plenum heaters are susceptible to damage from a low feed flow which eliminates the cold cap and exposes them to radiant heat from the molten glass. Plenum heaters should be designed to accept the maximum melter plenum temperature expected to occur during the life of the melter. Duratek test melters have been held under hot idle conditions for extended times by using the bubbler feature to create an insulating layer of high bubble content frozen glass on top of the melt and lowering melter power.

Table 9-4. GTS Duratek, Inc. Melter - Findings.

Item	Cause and consequences	Recommendation
Offgas system		
Melter offgas	A major cold-cap disruption → overpressure condition → melter and duct rupture and cell contamination	Engineering item: additional test may be needed to determine peak pressures
	A major cooling water leak from the feed nozzle → overpressure → and cell contamination	Engineering item: design melter offgas to handle this condition
Plenum heater		
Plenum heater	Loss of cold cap → exposes the plenum heater to radiant heat from molten glass → loss of plenum heater	Engineering item: reliable monitoring and control system to ensure plenum heaters <900 °C
Bubbler		
Pressure loss	Pressure loss in main bubbler → molten glass fills or plugs bubbler → replace bubbler	Engineering item: ensure adequate pressure and flow to bubbler
Excess flow	Airlift bubbler gas flow exceeds acceptable glass discharge rate → glass spill	Engineering item: size components for prevention

The loss of bubbler pressure, to either the airlift or main bubblers, allows molten glass to flow through the small bubbler orifices and plug the bubbler. Because bubbler replacement is expected to exceed 10 days, it has a significant impact on production, particularly if all the bubblers are affected. A reliable gas supply is necessary to prevent this condition.

Excess gas to the airlift bubblers from a control system malfunction could cause excessive glass discharge rates. It is recommended that the design limit the maximum airlift bubbler gas rate so acceptable glass discharge rates are not exceeded.

9.1.2.5 Envitco Melter Findings. The Envitco melter findings are summarized in Table 9-5. The water-cooled shell poses a serious threat to the melter integrity due to either a melter pressure surge or a cooling water loss. In the original full-scale melter concept provided by Envitco, ~600 cooling panels with individual inlet and outlet water lines comprise the outer melter shell. The melter integrity with the originally proposed replaceable panel design is potentially vulnerable to a cooling water loss at any local panel due to a mechanical impact, a leak, or pluggage. If cooling is lost, the skull could thin and a potential rupture at the site of the defective panel may occur. This loss appears likely during the melter life considering the number of panels and their associated lines and connections.

Envitco later modified this design using fewer large, high-temperature alloy plates for the melter shell. Envitco believes this design would withstand a loss of cooling long enough to allow the melter to cool. This design modification would help to lower the probability of cooling water loss but would not ensure complete prevention. Further, the acceptability of any loss of cooling water has not been established. Yet to be addressed is the possibility of unacceptable cell contamination due to panel rupture which might result from conceivable pressure excursions (e.g., melter offgas pluggage or water leaks in the plenum heaters, electrode holders, etc.).

The 'salt tap' system is a concern. The connection between the melter and the vessel must be reliable; otherwise, a molten salt could leak out to the melter floor. Engineering controls must be developed to ensure the reliability of the connection. Additionally, it is recommended that the salt tap catchment vessel be sized for the worst-case slag overflow condition to avoid a spill in the event of a level control malfunction.

The Envitco design has a bottom drain valve that may be used to periodically drain accumulated sludge or metals from the melter, or drain the melter at end of life or in emergency situations. Refractory material accumulation in the bottom of the melter's conical section may prevent glass evacuation through the bottom drain valve. The reliability of the bottom drain for emergency draining of the melter is an issue because the operation would be performed using remote equipment in a short duration of time. A study is recommended to investigate the impact of refractory material accumulation on draining.

Table 9-5. Envitco, Inc. Melter - Findings.

Item	Cause and consequences	Recommendation
Melter integrity/leak		
Cooling water system	Cooling water panel above glass line, electrode holder, or feed nozzles leak → high steam generation → excess steam flow in melter offgas	Engineering item: design melter offgas to withstand this flow
	Cooling water loss from mechanical impact, or cooling water panel line pluggage or leak → shell rupture	Engineering item: redesign the cooling water system to reduce the quantity of cooling water circuits
Salt tap connection	Connection between the melter and the catch tank leaks → glass spill	Engineering item: highly reliable connection
Salt containers	Glass level control system malfunction → excessive flow to salt containers → overflow of containers	Engineering item: control and monitoring system for prevention; catch tank sizing for mitigation
Bottom drain		
Bottom drain outlet	Refractory material accumulation → inability to drain glass to special vessel during an emergency condition such as potential melter rupture	Development item: identify refractory material that is compatible with the glass; ensure that refractory loss does not result in drain plugging
Melter plenum		
Cold cap	Cold-cap bridging → melter shutdown	Engineering item: provide plenum heaters in design for cold-cap management, startup, organic destruction, and prevention of bridging Engineering item: reliable monitoring and control to ensure plenum heaters remain <900 °C in the event of a loss of cold cap

The Envitco melter does not contain plenum heaters. An increased potential for cold-cap bridging was considered to be an issue without plenum heaters. Bridging is the phenomenon of solidifying the glass just below the cold cap. If this occurs, it could create a rigid barrier across the top of the melter to prevent feed material from mixing with the molten glass. Installation of plenum heaters is recommended to provide the capability of melting the cold cap should bridging occur. Without plenum heaters, additional thermal treatment of the offgas may be needed for organics destruction.

9.1.2.6 Vectra Melter Findings. The Vectra melter findings are summarized in Table 9-6. A cooling water loss caused by a mechanical impact, pump system failure, or poor water quality can eliminate the skull and expose the shell to overheating and rapid corrosion. This scenario is important in defining the design requirements of the vessel shell and cooling water system.

The bottom induction-heated drain valve may plug during operation. Because of the small throat of the induction-heated valve, it is susceptible to plugging by high melting temperature sludge or refractory material accumulation. There is also a scaleup concern that reliable flow control may

Table 9-6. Vectra Technologies, Inc. Melter - Findings.

Item	Cause and consequences	Recommendation
Melter cooling		
Melter offgas	A major cooling water leak from the electrode holder → overpressure → and cell contamination	Engineering item: design melter offgas to handle this condition
Melter shell	Mechanical impact, pump failure, poor water quality → loss of skull → shell experiences overheating → melter rupture	Engineering item: design of cooling water system components for reliable delivery
Outlet drain		
Outlet induction-heated valve	Refractory material accumulation → cold spots → inability to drain glass to special vessel during an emergency condition such as potential melter rupture	Development item: identify refractory material that is compatible with the glass; ensure that refractory loss does not result in drain plugging
Plenum heater		
Cold cap	Cold-cap bridging → melter shutdown	Engineering item: provide plenum heaters in design for cold-cap management, startup, organic destruction, and prevention of bridging Engineering item: reliable monitoring and control to ensure plenum heaters remain <900 °C in the event of a loss of cold cap

not be achievable for an induction-heated bottom drain that relies on heating and cooling of the glass to control the flow rate on a 50 tonne/day melter. The design should consider the use of a mechanical valve with a larger throat that is not as susceptible to refractory material accumulation.

The proposed full-scale Vectra melter does not include plenum heaters. As previously discussed for the Envitco melter, including plenum heaters is recommended for cold-cap control and also may be beneficial for organic destruction.

The other items mentioned in Table 9-6 can be incorporated with current technology.

9.1.2.7 WSTC Plasma Arc Melter Findings. The WSTC plasma arc melter findings are summarized in Table 9-7. A cooling water loss caused by a mechanical impact, pump system failure, or poor water quality can eliminate the crucible skull and expose the shell to overheating and rapid corrosion. This scenario is important in defining the design requirements of the vessel shell and cooling water system.

The design of this melter results in a relatively large, ~3%, particulate carryover from the tuyeres into the plenum space. This carryover could cause frequent plugging of the offgas lines.

Table 9-7. Westinghouse Science and Technology Center Plasma Arc Melter - Findings.

Item	Cause and consequences	Recommendation
Melter integrity		
Cooling water system	A major cooling water leak → overpressure → and cell contamination	Engineering item: design melter offgas to handle this condition
	Mechanical impact, pump failure, poor water quality → loss of skull → shell experiences overheating and corrosion → melter rupture	Engineering item: design of cooling water system components for reliable delivery
Offgas system		
Plenum space	Relatively large (3%) particulate carryover into plenum space and offgas lines → offgas flow restriction → high maintenance frequency and loading of ejector venturi scrubber system	Development item: develop and test offgas cooling and particulate recycle system that prevents plugging or restriction of flow or excessive buildup in ejector venturi scrubber

9.2 ENVIRONMENTAL EVALUATION

Six Phase 1 glass melter technologies for vitrification of Hanford Site LLW were evaluated based on environmental criteria. The criteria used in the evaluation include compliance with potential permitting requirements, melter operation, and glass product characteristics.

9.2.1 Scope

The environmental evaluation focused exclusively on the melters and the secondary streams generated by the melters under normal operations. Offnormal or upset conditions were addressed only briefly, in terms of melter surges potentially impacting emission rates. The environmental analysis was based on available Phase 1 cold test data, Aspen Plus* flowsheet simulation data, vendor information, and technical information reports.

The environmental impacts of a system generally can be assessed by evaluating solid waste generation, liquid effluent generation, and air emissions. The only expected streams exiting the melters under normal operation were a glass product stream and an air emission stream. Therefore, the analysis of secondary waste streams focused on air emissions before treatment.

The environmental evaluation did not attempt to evaluate melter offgas treatment systems because the objective of the analysis was to focus on the melters, independent of the offgas treatment systems. Therefore, secondary waste streams generated from melter offgas treatment systems were not

*Aspen Plus is a trademark of Aspen Technology, Inc.

addressed in the environmental evaluation. Offgas treatment systems were addressed to the extent that higher melter emissions could require additional abatement to remain within allowable emission limits.

9.2.2 Analysis

The melters were evaluated based on the following environmental criteria:

- Potential permitting classification under WAC 173-303, "Dangerous Waste Regulations"
- Compliance with the incinerator standards of WAC 173-303-670
- Emissions of criteria pollutants
- Radionuclide emissions
- Fuel and other hazardous material usage requirements
- Melter surge magnitude
- Percent volume reduction achieved by the melter
- Glass leachability.

Permitting classification refers to the potential permitting classification of the melter as a miscellaneous unit (WAC 173-303-680) or as an incinerator (WAC 173-303-670). There may be advantages to permitting the melter as a miscellaneous unit; therefore, those melters that have a higher potential of being permitted as a miscellaneous unit are favored somewhat based on this criterion.

Incinerator permitting standards include the following: (1) 99.99% destruction and removal efficiency for principal organic dangerous constituents (PODC) or dangerous combustion byproducts (WAC 173-303-670(4)(a)(i)); (2) stack emissions of dangerous combustion byproducts $\leq$0.01% of the total mass feed rate of PODCs fed into the incinerator (WAC 173-303-670(4)(b)); (3) HCl emissions $\leq$1.8 kg/h or 1% of the HCl in the stack gas before entering any pollution control equipment (WAC 173-303-670(4)(c)(i)); and (4) particulate emissions $\leq$180 mg per dry standard cubic meter (WAC 173-303-670(4)(c)(ii)).

Criteria pollutants include particulates, SO_2, NO_x, CO, volatile organic compounds, lead, fluorides, sulfuric acid mist, total reduced sulfur (including H_2S), and H_2S. Melters that minimize the generation of criteria pollutant emissions, as well as other regulated pollutants, are preferable.

Radionuclide emissions refer to projected emissions of radionuclides from the melter and the resulting dose consequences. Melters that minimize emissions of radionuclides and, therefore reduce the degree of control required, are preferred.

Fuel and hazardous material usage requirements refer to the quantity and types of hazardous materials used in the process. Melters that minimize the use of hazardous materials are favored based on this criterion.

Melter surge magnitude refers to the magnitude of melter surges resulting from gas buildup in the melter pool. Increased hourly emissions may result from occasional melter surges. Melters that have lower potential surge magnitudes are favored over the other melters.

Percent volume reduction refers to the percentage that the melter feed volume is reduced following conversion to glass. On an equivalent waste loading basis, higher volume reduction percentages are favorable.

Glass leachability refers to the performance of the glass under the TCLP (Method 1311 of EPA/SW-846 [EPA 1986]). If the extract from a representative sample of the glass contains any of the contaminants listed in the toxicity characteristic list of WAC 173-303-090(8), at concentrations equal to or greater than the respective values, the glass will exhibit the toxicity characteristic and be regulated as a dangerous waste.

9.2.3 Conclusions

Based on available information, the environmental criteria considered in this evaluation did not significantly discriminate among the six melter technologies evaluated. However, minor differences existed among the melters in the following areas: potential permitting classification, melter offgas characteristics, the degree of control required to comply with incinerator standards in WAC 173-303-670, and the potential melter surge magnitude. The results of the analysis are summarized in Table 9-8.

The following factors are considered favorable from an environmental standpoint.

- The melter is more likely to be permitted as a miscellaneous unit than as an incinerator.
- The degree of additional control required to comply with WAC 173-303-670 incinerator standards is minimized.
- Melter emissions are minimized.
- Secondary waste generation is minimized.
- Hazardous material usage is minimized.
- Fuel requirements are minimized.
- The glass product meets TCLP.
- Percent volume reduction is maximized.

Table 9-8. Environmental Criteria for Low-Level Waste Melter Comparative Analysis. (3 sheets)

Melter description		Potential permitting requirements						
Melter vendor	Mode of operation	Potential permitting classification[a]	Cl emissions (before treatment)[b] (kg/yr)	Particulate emissions (before offgas treatment)[c] (kg/yr)	Criteria pollutant emissions (before offgas treatment)[d] (kg/yr)			Estimated dose from ^{137}Cs, ^{90}Sr, ^{90}Y, and TRU (mrem/yr)[e]
					NO_x	SO_2	CO	
B&W	Cyclone combustion 1200-1350 °C	Miscellaneous Unit or Incinerator	3.1E+05	4.9E+06	5.9E+06	1.9E+05	9.3E+06	1.78E+06
WSTC	Plasma arc 1300 °C	Miscellaneous Unit or Incinerator	1.6E+05	1.1E+05	5.7E+05	6.0E+04	0	1.70E+05
Envitco	Joule-heated 1350 °C	Miscellaneous Unit	4.4E+03	1.8E+05	2.1E+06[f]	2.9E+04	0	1.98E+04
Duratek	Joule-heated 1150 °C	Miscellaneous Unit	5.8E+04	1.8E+05	7.9E+05	1.1E+04	0	9.1E+04
USBM	Joule-heated 1300 °C	Miscellaneous Unit	1.6E+05	2.3E+06	6.4E+05	5.0E+04	0	8.92E+05
Vectra	Joule-heated 1200-1450 °C	Miscellaneous Unit	4.4E+03 (includes calciner)	2.1E+05 (includes calciner)	2.9E+05 (slurry fed)	2.9E+04 (includes calciner)	0	1.98E+04

Table 9-8. Environmental Criteria for Low-Level Waste Melter Comparative Analysis. (3 sheets)

Melter vendor	Melter operation				Glass product	
	Mode of operation	Fuel requirements	Designation of glass additives[g]	Melter glass inventory per unit of throughput[h]	Percent volume reduction[i]	Glass meets TCLP[j]
B&W	Cyclone combustion 1200-1350 °C	Natural gas	Additive components Nonregulated	0.08	Equivalent	Yes
WSTC	Plasma arc 1300 °C	None	Additive mixture D002[k]	0.01	Equivalent	Yes
Envitco	Joule-heated 1350 °C	None	Additive components Nonregulated	2.2	Equivalent	Yes
Duratek	Joule-heated 1150 °C	None	Additive mixture D002	0.54	Equivalent	Yes
USBM	Joule-heated 1300 °C	None	Additive mixture WT02	0.80	Equivalent	Yes
Vectra	Joule-heated 1200-1450 °C	None	Additive components Nonregulated	1.3 (slurry fed)	Equivalent	Yes

[a]Refers to permitting classification per WAC 173-303-670, "Incinerators," or WAC 173-303-680, "Miscellaneous Units."

[b]The HCl emission limit is a condition of dangerous waste incinerators (WAC 173-303-670(4)(c)(i)). An incinerator burning dangerous waste and producing stack emissions of more than 1.8 kg/h of HCl must control HCl emissions such that the rate of emission is no greater than the larger of either 1.8 kg/h or 1% of the HCl in the stack gas before entering any pollution control equipment. The numbers in the table represent the total Cl emissions from the melter before offgas treatment to provide an indication of the extent of treatment required to achieve the required HCl emission limits. Speciation data on Cl are not available at this time. The numbers are based on Aspen Plus (trademark of Aspen Technology, Inc.) flowsheet data for full-scale facilities using available test data.

[c]The particulate emissions limit is a condition of dangerous waste incinerators (WAC 173-303-670(4)(c)(ii)). Particulate matter must not be emitted from the stack in excess of 180 mg per dry standard cubic meter (0.08 grains per dry standard cubic foot) when corrected for the amount of oxygen in the stack gas according to the formula:

$$Pc = \frac{(Pm \times 14)}{(21-Y)}$$

where:

Pc = Corrected concentration of particulate matter, mg/dscm

Pm = The measured concentration of particulate matter, mg/dscm

Y = The measured concentration of oxygen in the stack gas, in volumetric percent.

The numbers in the table represent the particulate emissions from the melter before offgas treatment to provide an indication of the extent of treatment required to achieve the required particulate levels. The numbers are based on Aspen Plus flowsheet data for full-scale facilities using available test data.

Table 9-8. Environmental Criteria for Low-Level Waste Melter Comparative Analysis. (3 sheets)

[d]The numbers in this column represent the estimated annual emissions of NO_x, SO_2, and CO from the melter before offgas treatment to provide an indication of the extent of treatment required to remain under the required criteria pollutant significance levels. The NO_x emissions are based on NO_x yield values from preliminary Phase 1 test results. The NO_x yield values were applied to the melter feed to derive the estimated NO_x emissions from a full-scale facility. The NO_x emissions are expressed as NO_2. The SO_2 and CO emission estimates are based on Aspen Plus flowsheet data.

[e]Preliminary unmitigated dose consequences are calculated for the following radionuclides: ^{137}Cs, ^{90}Sr, ^{90}Y, and TRU. The dose consequences are calculated using WHC-EP-0498, Unit Dose Calculation Methods and Summary of Facility Effluent Monitoring Plan Determinations, J. M. Nickels, Westinghouse Hanford Company, Richland, Washington, 1991. The total dose expected from uncontrolled air emissions of these radionuclides was calculated by multiplying the release quantity in curies for each radionuclide by the corresponding unit dose factor and adding the contributions.

[f]Envitco emission values are based on data obtained from melting dry feed prepared by the Bepex Unison drying process, which showed poor NO_3^- destruction efficiencies. Envitco is evaluating alternative feed preparation processes to lower NO_x emissions.

[g]With the exception of the USBM, the waste predeterminations were based on the oxide form of borate rather than the hydrated form (boric acid). Although this constituent is routinely reported in the oxide form (B_2O_3; borate, boric anhydride), the hydrated form (boric acid) is typically used in preparing glass formers. The oxide form (boric anhydride) is nonregulated; however, boric acid is assigned a toxic category 'D.' Therefore, all the glass additive mixtures, with the exception of Duratek, could potentially be regulated for toxicity and, hence, assigned the WT02 code.

[h]The numbers in this table represent the glass inventory in the melter under steady-state conditions per unit of throughput for full-scale facilities. This provides an equivalent basis for comparison. The number is intended to provide an indication of the magnitude of melter surges resulting from gas buildup in the melter pool. The smaller the number, the smaller the expected magnitude of the melter surge.

[i]The percent volume reduction is assumed to be equivalent for all the melters and is, therefore, not a discriminator among melters.

[j]All the glass formulations are expected to pass the TCLP test; therefore, this criterion is not a discriminator among melters.

[k]The predetermination for the WSTC frit mixture indicated that the mixture could be designated D005 for toxicity due to barium. It was later determined that the barium was a contaminant in the frit used in the WSTC tests. The TCLP tests of the frit and of the product glass did not yield leachates with barium concentrations in excess of 100 mg/L. In addition, the predetermination of the WSTC glass formers has been revised to include the D002 code. The D002 code was not initially assigned to the WSTC glass formers. The D002 code is assigned on a conservative, worst-case basis for corrosivity.

B&W = Babcock & Wilcox
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
TCLP = Toxic characteristic leaching procedure
TRU = Transuranic
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.
WSTC = Westinghouse Science and Technology Center

A comparative evaluation of the melters was performed in accordance with the above criteria. Based on available information and the results of the melter assessment against the applicable environmental criteria, the melters that appear optimal in this evaluation are as follows:

- Joule-heated melters: Duratek, Vectra
- Non-Joule-heated melters: WSTC.

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10.0 EVALUATION SUMMARY

After Phase 1 testing was completed, Phase 1 results and Phase 2 vendor proposals were evaluated and recommendations made for Phase 2 testing following a preapproved Evaluation and Phase 2 Selection Plan. The evaluation proceedings, findings, and recommendations are summarized in this section.

10.1 EVALUATION BOARD

A 12-person Evaluation Board was assembled to evaluate Phase 1 testing results and Phase 2 vendor proposals and to make recommendations for Phase 2 testing. The Evaluation Board member functions were as follows.

- Board Chairperson--Directed Evaluation Board activities to ensure that the Board evaluations were conducted in a fair, thorough, and timely manner.
- Scoring Board Members--Five persons with vitrification and/or nuclear processing background who scored the vendor technologies to preestablished selection criteria. Four of the Scoring Board members were WHC senior technical staff and the fifth member, selected for his independent expertise in nuclear waste processing, was brought in from another company.
- Advisory Panel--Four independent experts (two commercial glass industry consultants, one nuclear process consultant with Defense Waste Processing Facility experience, and one senior staff member from the SRS).
- WHC Technical Advisor--Was the WHC lead engineer for the LLW vitrification vendor demonstration testing and had participated in all seven Phase 1 vendor tests.
- WHC Procurement Advisor--Was the lead WHC procurement and contract specialist for the LLW vitrification vendor demonstration testing program.

In addition to the above Evaluation Board members, a DOE observer was present to observe the presentations and much of the Evaluation Board deliberations.

10.2 EVALUATION PROCEEDINGS SUMMARY

The full Evaluation Board proceedings were conducted from May 8-19, 1995. Scoring was completed and Phase 2 work scope recommendations were drafted by the Scoring Board members from May 22-26. All Evaluation Board members were provided copies of the Evaluation and Selection Plan, vendor Phase 1 preliminary test reports, and vendor Phase 2 proposals for review 2 weeks before the Evaluation Board proceedings began on May 8. The following is a summary agenda of the Evaluation Board proceedings.

May 8, 1995--Presentations (~1 hour each) by the WHC cognizant engineer for each Phase 1 vendor test. These presentations covered material similar to that provided for each vendor test discussed in Section 4.0 of this document.

May 9, 1995--Morning presentations on the following:

- Process flowsheet evaluations
- Facility configuration and cost studies performed by Fluor.
- Remotability, operability, and maintainability evaluations.

Afternoon, closed discussions.

May 10, 1995--Presentations on the following:

- Phase 1 melter mass balance results
- Phase 1 product glass characterization results
- Safety and environmental assessments
- Assessment of vendor quality assurance programs.

May 11, 1995--Closed Evaluation Board deliberations; prepared questions for vendors to address during vendor presentations.

May 12, 1995--Vendor presentations and discussions with Envitco (morning) and USBM (afternoon).

May 15, 1995--Vendor presentations and discussions with Vectra (morning) and WSTC (afternoon).

May 16, 1995--Vendor presentations and discussions with Duratek (morning) and B&W (afternoon).

May 17, 1995--Closed Evaluation Board deliberations; developed technical issues list.

May 18, 1995--Consensus rating and scoring of vendor technologies by full Evaluation Board to the developed technical issues list.

May 19, 1995--Last day for Advisory Panel members; Advisory Panel recommendations prepared.

May 22-26, 1995--Weighting factors for scoring criteria developed by Scoring Board members, technologies scored to preestablished selection criteria, and recommendations developed for Phase 2 testing.

10.3 RANKING AND SCORING

Scoring criteria were developed as part of the preapproved Evaluation and Phase 2 Selection Plan. Weighting factors for these criteria were to be

developed by the Scoring Board members before final scoring. A preliminary consensus ranking and scoring to a list of developed technical issues was done by the full Evaluation Board before final scoring. Because no Phase 2 proposal was received from PEI, and PEI was not being considered for Phase 2 testing, the PEI technology was not included in the ranking and scoring.

10.3.1 Ranking and Scoring to Technical Issues List

During the evaluation process, the Board developed a list of technical issues and conducted a preliminary ranking and scoring of the vendor technologies to these issues. The primary value of this activity was to serve as a framework for moderated discussion of the strengths and weaknesses of the technologies, and to help identify and build a consensus on issues that the Board found to be relevant.

The Board developed a list of 22 technical issues and qualitatively ranked each vendor technology from 1 to 6 on each issue. The importance of each issue was then weighted and each technology re-ranked on a scale of 1 to 10 on each issue to provide broader discrimination in the rankings. Significant discussions preceded Board consensus ratings on several issues. The relative ranking factors on each issue (1 to 10) were then multiplied by the issue weighting factors (also 1 to 10) to derive a vendor technical issue scoring. The developed issues, ranking, and scoring details are provided in the Advisory Panel report in Appendix C (Tables C-1, C-2, and C-3). The resulting total scores for each vendor technology are as follows:

Vendor technology	Score
Envitco	1,246
Vectra	1,094
Duratek	1,263
USBM	1,001
WSTC	782
B&W	572

10.3.2 Scoring to Selection Criteria

Following the preliminary consensus ranking and scoring on developed technical issues, the Scoring Board members developed weighting factors for the preestablished Phase 2 selection criteria as required by the Evaluation and Phase 2 Selection Plan. The Phase 2 selection criteria were derived from those developed for the original Request for Proposal (WHC 1994), which are also provided in the SOW, Appendix B (Wilson 1994). A sample score sheet with the Phase 2 selection criteria and weighting factors is provided as Figure D-1 in Appendix D.

The cost criteria and the quality assurance criteria were given a zero for weighting factors. The Phase 2 work scope to be recommended was in most cases significantly different from that costed in Phase 2 vendor proposals and the Board decided that the cost for the recommended work for each demonstrator could not be determined on an equitable basis. A 5% cost weighting was considered and it was later noted that at 5% weighting, cost scoring would not have changed the final standings.

Detailed anonymous scoring by the five Scoring Board members for each criterion and vendor is provided in Appendix D. The average scores by criteria category and totals are presented in Table 10-1.

10.4 EVALUATION BOARD OBSERVATIONS

The Evaluation Board identified numerous generic and technology-specific issues. The former provided a basis for formulating Phase 2 needs. The technology-specific issues were the major discriminators for vendor evaluation.

10.4.1 General Issues

Several issues were common to the various technologies and were a significant factor in developing work scope recommendations for the Phase 2 program. Included in these observations were consideration of such common aspects as shielding requirements, feed system simplification, radioactive testing, and product glass specifications. Other considerations, including remotability, mass balance, and melter characteristics, while of general interest, weigh somewhat differently for each of the technologies involved.

10.4.1.1 Shielding and Remote Handling Requirements. Shielded remote handling capabilities are recommended for feed processing equipment that contains LLW, the melter, and primary offgas equipment. The extent and complexity of in-cell equipment should be minimized.

At the time of the fourth amendment to the Tri-Party Agreement (Ecology et al. 1994), an evaluation of worker radiation exposure, radionuclide separation, and shielding requirements was requested because it was believed that a lightly shielded, contact-maintained LLW vitrification facility would be feasible. This evaluation has now been completed for Cs DFs

Table 10-1. Average Scores by Category.

Category	Selection criteria average scores by category						
	Points available	Envitco	Vectra	Duratek	USBM	WSTC	B&W
A. Technical merits	75	66.92	56.28	61.72	43.28	25.20	12.48
B. Phase 2 proposal	10	9.64	4.04	9.72	7.36	4.12	1.88
C. Seller qualifications	15	13.80	10.44	14.04	9.00	5.16	4.14
Totals	100	90.36	70.76	85.48	59.64	34.48	18.50

B&W = Babcock & Wilcox
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.
WSTC = Westinghouse Science and Technology Center

in pretreatment ranging from the baseline flowsheet assumption of 100 to 10,000, together with various DFs for other significant radionuclides (Sr, Eu, and Co). Planned contact maintenance is not feasible, even for the Cs DF 10,000, Sr DF 100 case, irrespective of nuclide accumulation due to effects such as recycle from offgas and diffusion in refractories. The Board therefore concluded that shielded remote handling facilities would be required for LLW feed, melter, and primary offgas equipment. As a consequence of this, the Board also concluded that the extent and complexity of in-cell equipment assumes more importance and should be minimized.

The evaluation of radiation exposure, nuclide separation, and shielding had only recently been completed and the vendors did not have the benefit of this information during their Phase 1 work. The Board took this into account when evaluating full-scale plant concepts, which often advocated contact maintenance. During Phase 2, however, vendors will be instructed to place emphasis on remote handling and minimization of in-cell equipment when developing concepts for the full-scale plant.

10.4.1.2 Feed Method. Several methods for melter feed preparation and melter feeding were tested during Phase 1 and/or are proposed for testing during Phase 2. The Board concluded that batched slurry feeding is the most promising approach for most melter technologies. Moist mix-in-the-charger feed and dry feed should be considered as first and second alternatives to batched slurry feed. The possible exception is the USBM carbon electrode melter where slurry or wet feed has not been demonstrated. Alternative melter feed systems considered during Phase 1 testing are discussed in the following sections.

10.4.1.2.1 Dried and Prereacted Feed. Envitco and USBM propose to use dry, denitrated feed for baseline testing. Both would use feed prepared by USBM via a process developed and demonstrated during Phase 1 testing. Dry feed is commonly preferred in commercial cold-top, glass-melting processes and generally provides the lowest loss of volatile feed components. Proposed feed preparation equipment includes a ribbon blender, ring pelletizer, a belt dryer, and mechanical feeders such as feed chargers. Space requirements, equipment complexity and reliability, and remote operation and maintenance of this equipment in a shielded facility were judged by the Board, and especially the Advisory Panel, to present serious problems to the extent that such operations would likely prove impractical.

10.4.1.2.2 Calcined Feed. Vectra, through a subcontractor (Procedyne, Inc.), demonstrated calcining of LLW simulant and glass formers together in a fluid-bed calcining process during Phase 1 testing. Calcining was not proposed by Vectra for Phase 2 for the following reasons: development required, low processing rates of available pilot equipment, low melt rates achieved with the calcined product, and better-than-expected results with slurry feeding.

10.4.1.2.3 Slurry Feed. Envitco, Vectra, and Duratek successfully demonstrated feeding batched slurry and all three vendors achieved better-than-expected melting rates with slurry feed. Although mass balances for volatile feed components such as halides were not as good as with dry feed cold-top operation (~50% Cl volatility for Phase 1 slurry feeding at Duratek versus <10% for Envitco), the Board determined that volatilized components

(excluding I or C) could be scrubbed by the offgas system and recycled. The Board was sufficiently encouraged by Phase 1 slurry feeding results to recommend that slurry feeding be given priority over dry feeding for Phase 2 testing. A batched thick slurry ('paste') was used for B&W Phase 1 testing. Such a feed condition may represent the best balance of maximum reliability and minimum equipment.

10.4.1.2.4 Moist Mix-in-the-Feed Charger. Mixing dry nonradioactive glass-former materials with the radioactive liquid LLW stream in the feed charger requires minimal radioactive feed processing equipment. Mixing liquid and dry feed components in a feed charger that directly feeds the melter has been demonstrated by PEI, WSTC, and by Clemson University. A disadvantage is that two separately metered streams, LLW and glass formers, need to be independently metered to control feed composition, thus increasing the risk that out-of-specification feed composition could be fed to the melter, as compared to a batched slurry process. A variation on this feeding approach was used by WSTC during Phase 1 testing in which separately metered streams of glass-former frit and liquid LLW simulant were mixed in a Moyno pump which feeds directly to the melter tuyere. Failure to correctly meter the LLW and frit streams may have contributed to problems in closing the mass balance and to variations in glass composition during WSTC Phase 1 testing. If proven, this system would further minimize the amount of required in-cell equipment.

10.4.1.2.5 Separate Feeding of LLW and Glass Formers. Duratek proposes, as a process option, to separately feed liquid LLW and bagged pre-batched dry glass formers to the melter. The bagged glass formers would directly enter the melter from the top via chutes. Duratek expressed confidence that its bubbler system adequately mixes to give a homogeneous glass composition. Individual Board members were skeptical about the adequacy of mixing, process control, and effects on overall melting and refining rates. However, this system is simple and attractive because it requires a minimum amount of radioactive mechanical equipment.

10.4.1.3 Mass Balance and Recycle. As discussed in Section 7.0, Phase 1 test data demonstrated large differences among melters in the fraction of feed components that report to the offgas stream. This material either must be recycled to the melter feed or separated as a secondary waste stream.

The Joule-heated melters achieved the lowest losses to the offgas as represented by Envitco, Vectra, and Duratek. Vectra and Duratek tests showed higher losses than did the Envitco test, likely because Envitco ran a complete cold-top coverage with dry feed. Complete cold-top coverage was not obtained in the slurry-fed Duratek test, or with either dry or slurry feeding in the Vectra test. Data from the Vectra test indicate that selective volatility losses were greater with slurry feed than with dry feed. Losses of Na, K, and B likely were higher with Vectra than with Duratek because of a higher melting temperature (>1450 °C for Vectra versus 1150 °C for Duratek). However, selective losses (particularly halides) also appear to be increased in the Duratek melter because bubbling was used to increase the melting rate.

Losses to the offgas also were high for USBM Run 1. However, offgas losses were improved during Runs 2 and 3. Run 3 used larger-diameter electrodes to reduce electrode current density and was conducted at a lower melting temperature. The latter test data suggest that if the USBM melter can

be run at steady state in a cold-top operating mode, selective component losses may be of a reasonable level for recycle, but may still be greater than with cold-top Joule melters. Additional testing with the USBM electric arc melter is needed to confirm that acceptable volatility and entrainment losses can be achieved.

Clearly the high-energy 'hot-top' melters, as represented by WSTC and B&W, have much higher loss of feed components to the offgas than do the cold-top dry or slurry-fed Joule-heated melters as represented by Envitco, Vectra, and Duratek. If a large fraction of a component partitions to the offgas, recycle may be impractical, thus implying the need for separation of a secondary waste stream to handle buildup. Recycle of a large fraction of a major component is also a process control issue that complicates the production of a consistent target glass composition. Large losses to the offgas in the WSTC and B&W tests, along with fundamental considerations of the glass-forming mechanisms in these technologies, were considered by the Board to be a serious issue for these melter technologies. A large amount of testing and development work is expected to be needed to achieve a complete integrated process system, based on the WSTC and B&W technologies, that can be incorporated into a production plant with a reasonable degree of confidence.

10.4.1.4 Remotability, Operability, and Maintainability. Duratek's well-established Joule-heated melter concept is stable in operation and has no moving parts. Assuming that the central electrode proposed by Duratek for the full-scale is successfully demonstrated, the Duratek system is highly rated based on operability and maintainability criteria. Bubbler life is also undemonstrated as yet but, if necessary, remote replacement is not considered difficult. The melters are large and will have to be moved horizontally, probably on rails, through the cells during installation and replacement. Detailed methods must be carefully engineered and executed, but acceptable operating efficiency should not be compromised if the anticipated life of at least 3 years is achieved.

The Envitco melter concept is also highly rated. Remote methods for feeding and replacing the molybdenum electrodes need to be developed but should not be difficult. Melter replacement considerations are similar to those for the Duratek melter.

The Vectra concept causes more concern, mainly because it depends on the bottom drain for controlled discharge, a concept that is undemonstrated at high throughputs. The use of contact maintenance on the shielded melter top as proposed by Vectra could be more troublesome than envisioned and a more detailed examination of methods and predicted dose rates is needed. The melter replacement concept also needs to be better developed and evaluated in more detail.

The USBM melter concept has features similar to the Joule-heated melters and may be easier to replace because it is smaller. Remote handling of the carbon electrodes needs careful consideration, however. The proposed full-scale electrodes are large (61 cm diameter) and the consumption rate is high (estimated at 24 cm/day).

Failure rates will be high for the plasma torches in the WSTC concept and daily replacement of the torch subcomponents could be necessary in view of

30 torches being proposed for the plant. If contact maintenance is feasible, as assumed by WSTC, this replacement may not be too difficult. It is considered, however, that remote operation will probably be necessary; this will greatly increase the complexity of equipment at the already congested feed points and logistics may make daily plasma torch maintenance unattractive. If remote maintenance is necessary, tuyere life becomes another major concern. The WSTC proposed full-scale plant arrangement assumes that the cupola will not have to be replaced during the life of the plant, an assumption that carries considerable risk.

The B&W cyclone melter needs to be periodically shut down for replacement of refractory and studs, a procedure that involves welding. Although B&W has cited time intervals up to 7 years for such repairs, the maintenance frequency for LLW vitrification is unknown. The cyclone combustors are usually inspected annually and repaired as needed. It is probably not feasible to carry this out remotely and consequently the cyclone would have to be replaced, a complex operation in view of the interactions with the pressurized water/steam cooling system. Such a replacement is considered undesirable on an annual basis. The B&W offgas system is much larger than those of other vendors with consequentially increased difficulty for maintenance and replacement operations.

10.4.1.5 Maturity of Technology for Vitrification. While glass melting or vitrification has been a manufacturing technology for several thousand years, the use of larger furnaces that produce substantial volumes of glass is about a hundred years old.

The most common form of melter and the most mature glass-melting technology is the fossil fuel-fired regenerative tank furnace used in the container and flat glass industries in which hundreds of tons per day are melted by combustion heat in refractory-lined pools. These furnaces use dry feed and overflow drains. This type of vitrification is inappropriate for LLW vitrification for a number of reasons, the most compelling being the large gas throughput, large area, and contact maintenance required. Also, hot-top operation of such melters will aggravate volatility and entrainment issues.

Electric resistance or Joule-heated glass melters are a technology with ~50 years of experience. These melters are widely used in specialty glass melting, often in a vertical cylinder configuration with side or bottom electrodes. Dry feed is used, and the melters operate with a cold top and overflow drain spouts. The Pochet melter is a special subset of this category, using a water-cooled bowl usually with some refractory lining and diagonally entering top electrodes. This type of melter, often called a skull melter, is not widely used in the commercial glass industry. A few of these units were introduced in the United States ~20 years ago, and used in a fiberglass plant.

Arc melting with carbon electrodes has limited use for commercial glass production (i.e., mineral wool) although it is a well-established technology in the steel industry where it is considered quite mature. Most mini-mills that use scrap metal feed use carbon electrode electric arc melters.

Plasma melters have not been used for commercial glass melting and should not be regarded as a mature technology in that sense. A Westinghouse-supplied

plasma torch-fired cupola furnace is used in a General Motors foundry operation for remelting scrap iron. Plasma units also have been introduced in recent years for municipal waste vitrification where their performance is being studied. Plasma torches may show promise as startup heat sources for other melter technologies.

Cyclone combustion furnaces are not used for commercial glass melting. The B&W technology is derived from coal combustion technology for which B&W has more than 50 years of experience. This expertise includes service with Illinois high-Na, high-chloride coals which generate an ash similar to LLW glass. These furnaces have been used for fusing fly ash and vitrifying contaminated soils.

10.4.1.6 Glass Product Quality. Each vendor was free to choose or develop its own target glass formulation to be used for Phase 1 testing. The only requirements for the glass formulation provided in the SOW (WHC-SD-WM-RD-044 [Wilson 1994]) were that waste loading be ~25 wt%, and that normalized Na release measured by the PCT method at 90 °C be <1 g/m^2/day. Additional glass properties of interest include redox (Fe^{+2}/Fe), homogeneity, presence of unreacted material, devitrification, inclusions, or other defects.

Glass samples were characterized by Corning Engineering Laboratory Services, U.S. Geological Survey, and PNNL. Characterizations included composition analyses, homogeneity, inclusions, and PCT durability. A summary of selected observations from these glass sample analyses is presented in Table 10-2. Except for the presence of unreacted zircon batch material in the Duratek glass samples, the Joule-heated melters, in general, produced uniform homogeneous glass. The USBM glass was highly reduced with Fe^{+2}/Fe

Table 10-2. Summary of Product Glass Quality.

Vendor	Na PCT	Inclusions	Devit/ cords	Remarks
Envitco	Acceptable	None	Faint cords	Well-reacted/mixed (bubbles)
Vectra	Acceptable	Trace Ni, Mo, S particles	No cords to moderate cords	Well-reacted/mixed
Duratek (DM-1000)	Acceptable	0 to 2 vol% trace zircon	Faint cords	Contained unreacted zircon grains and bubbles
USBM	Acceptable	<1% Mo metal	Heavy cords	Reacted, poor mix, cordy/ reduced
B&W	Acceptable	Up to 10%	Refractory alterations/stones	Poor reaction and mixing, nonhomogeneous
WSTC	Acceptable	<1% trace zircon	Heavy cords	Reacted, poor mix, cordy

B&W = Babcock & Wilcox
Duratek = GTS Duratek, Inc.
Envitco = Envitco, Inc.
PCT = Product consistency test
USBM = U.S. Bureau of Mines
Vectra = Vectra Technologies, Inc.
WSTC = Westinghouse Science and Technology Center

approximately equal to 1, with some samples heavily corded. The WSTC glass appeared to contain amounts of dissolved refractory material and also was cordy. The B&W glass samples were the least homogeneous, with many fine bubbles, and contained inclusions that appeared to include undissolved refractory particles.

10.4.1.7 Similar Technologies--Envitco and Vectra. Phase 2 deselection criteria provided in the SOW (Wilson 1994) state that if two or more technologies tested during Phase 1 are judged to be similar with the exception of one or more special features, and the special features of one technology are judged to be clearly superior, that these special features may be used as a discriminator in choosing which of the similar technologies to test during Phase 2. The Board judged that Envitco and Vectra represented such similar technologies and that the overflow drain feature of the Envitco melter was clearly superior to the bottom drain feature proposed by Vectra for high-throughput LLW vitrification. Both Envitco and Vectra propose high-temperature-capable Joule-heated melters with top-entering molybdenum electrodes, both with water-cooled shells, and both claiming the formation of a frozen skull layer to extend melter life. Envitco would build the Phase 2 melter and lease it to WHC for testing. In the Vectra proposal, WHC would buy the Phase 2 melter. The lease arrangement proposed by Envitco was judged to be more cost effective and preferred to WHC buying the Vectra melter.

Envitco has built a 5 tonne/day melter of similar design (sidewall electrodes instead of top-entering electrodes) to that proposed for Phase 2 testing. This melter will be demonstrated for the vitrification of low-level mixed waste at the DOE Oak Ridge Site during fiscal year (FY) 1996. Because the Board is recommending slurry feeding for Phase 2 baseline testing of Joule-heated technologies, other than performance data related to the different drain concepts, of which the Board considers the Envitco overflow pour drain to be superior, few additional data needs would be satisfied by Phase 2 testing in both the Envitco and Vectra melter systems.

The Board also considered the melter engineering and related technical resources represented by Envitco and its affiliated companies TECO and KTG to be superior to that offered by Vectra, which has limited vitrification experience and is heavily reliant on consultants for vitrification expertise. The Board therefore recommended that Phase 2 testing of high-temperature-capable Joule-heated melter systems be performed by Envitco rather than Vectra. This recommendation is based on the foregoing considerations and not on Phase 1 performance or test data.

The Board further recognized Vectra's commercial experience in radioactive and LLW handling experience, and experience expected to be gained in its planned commercial LLW vitrification activities, to be unique strengths. The Board also recognized experience gained by Vectra's vitrification consultant on the performance of top-entering molybdenum and carbon electrodes in the vitrification of electric arc furnace dust at Oregon Steel Company to be of potential value. The Board therefore recommended that Vectra be brought into Phase 2 to provide (1) reporting based on its planned commercial LLW vitrification experience and information that may be available based on the Oregon Steel Co. experience, (2) reasonable engineering support to advance the

Vectra design concepts for a Hanford Site LLW vitrification system, and (3) a Phase 2 technical information report that describes its updated LLW melter system concepts.

10.4.1.8 Radioactive Testing. Preliminary Hanford Site LLW disposal performance assessment (PA) work indicates that Tc is the most important radioactive component relative to PA performance of the waste form. Technetium in its higher oxidation state (Tc_2O_7) is likely to volatilize during vitrification processing. The volatility of Cs may be enhanced by volatilization of cesium pertechnate ($CsTcO_4$). Because there are no nonradioactive forms of Tc, a surrogate with volatility behavior similar to Tc over a range of oxidation states is needed to evaluate Tc volatility during Phase 2 testing of the candidate melter technologies. Thermodynamic data suggest that Re may be a likely candidate to simulate Tc during vitrification. Preliminary crucible testing by PNNL indicates that Tc and Re show similar high-volatility behavior when dry reagent batch materials are vitrified under atmospheric redox conditions. Radioactive testing in a bench-scale melter is needed to verify that Tc and Re exhibit similar behavior over a range of likely redox conditions in a cold-top melter. Duratek proposes to use the DM-100 radioactive bench-scale melter system at Catholic University for this testing. Duratek also proposes to include other radionuclides of interest such as Np. The Board recommended that this work be performed as a priority objective during Phase 2 to confirm the use of Re as a surrogate for Tc in LLW simulants used in other Phase 2 testing activities.

10.4.1.9 Product Glass Requirements. The Board believed that a shortcoming of the LLW Disposal Program exists in the absence of established requirements for LLW glass performance and waste form configuration. The Board recognized that glass quality requirements are driven by programmatic concerns that, while outside the scope of the technology evaluation, may still have significant bearing on the technology selection decision.

Among the factors that affect the melter technology evaluation are product durability and phase stability (or devitrification) requirements that will constrain the range of acceptable glass formulations. A given melter technology also will impose constraints on the range of formulations that can be processed, such as melt viscosity, liquidus temperature, melt volatility, and maximum operating temperature. The Board was concerned that these two independent sets of constraints may not overlap sufficiently to provide a glass formulation envelope that is feasible from the standpoint of processability and product performance.

The final waste form also is expected to have a significant impact on the product quality control strategy. Some melter technologies are more amenable to accepting product recycle than others. The logistics of implementing feedback control will directly affect the technology selection decision.

In the absence of an established product quality specification, the Phase 1 testing selected a target waste loading of 25 wt% and required a normalized Na release rate of <1.0 g/m^2/day by the PCT method as indicators of reasonable melter testing glass formulations. These were arbitrarily selected criteria that are not derived from a PA of the total disposal system configuration.

Phase 1 testing showed that all the technologies were able to produce glass that met the durability benchmark. However, the Board was concerned that a more stringent PA-based durability requirement may dictate the use of formulations requiring process conditions that are outside the working range of some technologies.

The Board strongly recommended that the waste form disposal configuration and associated glass durability requirements for each disposal product option be firmly established before the final down-selection of LLW melter technologies is made. The disposal configuration and glass durability requirements should be derived from a peer reviewed, PA-guided disposal strategy approach that includes long-term geochemical, materials science, and glass processing considerations.

10.4.2 Technology-Specific Issues

Technology-specific issues are identified in the following discussions of each vendor's system. The analyses associated with these discussions were the principal considerations in the evaluation and ranking of the vendors.

10.4.2.1 Envitco. The Board considered the Envitco-proposed technology to be among the most mature of the technologies evaluated for glass making. The Board also highly rated the technical capabilities of Envitco and its affiliated companies (TECO and KTG). TECO has built ~125 large, cold-top commercial glass melters worldwide and is an established supplier of engineering services to the glass industry. In common with most of the other vendors, Envitco's lack of experience in designing equipment for remote nuclear applications was considered a weakness. However, Envitco expressed an interest in working with WHC, an Architect-Engineer contractor, or other organizations as required to adapt Envitco's technology to remote nuclear application.

Envitco also demonstrated slurry feeding during Phase 1 testing, but complete offgas data needed for mass balance calculations with slurry feeding were not obtained. However, the Board concluded that the Envitco technology, as an overall system, should provide the lowest offgas recycle requirements of any of the technologies evaluated with either dry or slurry feeds. The Board also believed that it would be desirable in the production facility to use electrodes that could be tilted into a vertical position for remote maintenance access.

The Envitco melter design has a relatively thin wall of corrosion-resistant refractory brick as the containment for the glass melt. Envitco plans to back this with water-cooled and segmented-metal shell plates. The Envitco design proposal claimed that melter life would be substantially extended (by years) by the formation of a glass/devitrified material skull layer on the water-cooled melter shell. The Board asked about operating experience with skull, and was told that there is no significant commercial glass-making experience. The Board expressed concern about the claims for long-term melter operation that depend on forming and maintaining such a skull layer.

10.4.2.2 Vectra. The Board recognized that Vectra's Joule-melting technology is among the most mature technologies available for LLW vitrification. The Vectra design also was recognized for the superior containment aspects of the melter shell (pressure vessel) and limited contact maintenance situation created by the use of fixed and removable shielding around the melter head. The Board also recognized that Vectra is a commercially experienced vendor of nuclear waste processing, packaging, and disposal services.

However, the Board was concerned about reliability of the bottom drain system proposed by Vectra and use of a bottom drain to regulate molten glass levels in the full-scale melter. An advisory Panel member noted that inductively heated (and Joule-heated) bottom drains have failed in the glass industry because these drains are typically designed for molten metals rather than glass. Molten metals have more predictable thermal hydraulic characteristics than glass. While a bottom drain is desirable for the occasional removal of sludge or molten metals, the Board considered this to be a risky approach for the removal of glass from the LLW production melter. The Board also recognized that it would be difficult, if not impossible, to perform any maintenance service on this drain valve. The Board also was concerned about long-term melter operation with a glass skull.

The Vectra melter produced good results during Phase 1 testing. Vectra demonstrated slurry feeding and dry feeding of calcined feed, with moderate volatility losses. While the LLW simulant could be calcined, Vectra also demonstrated that melt rates with the calcined product were generally lower than melt rates with slurry feed. The Board concluded that Vectra's technology is highly promising, but reliability could be improved with the use of an overflow side drain for normal glass pouring operations.

10.4.2.3 Duratek. The Board considered the Duratek technology for waste glass to be relatively mature. The Board also highly rated the technical capabilities of Duratek and its affiliate VSL-CUA, which provides excellent glass chemistry support. Duratek is rapidly amassing valuable experience in the vitrification of nuclear wastes, and results from its contracts at Fernald and at the SRS M-Area and this experience should be pertinent to the Hanford Site June 1996 LLW vitrification process selection activity. Duratek recognizes its weakness in the design of remote nuclear systems, but is actively addressing this weakness by pursuing affiliations with designers and operators having such capabilities.

The use of 'thick wall' refractory lining is conventional and well established, giving confidence in melter life. The side discharge using an airlift is also commended as simple, reliable technology.

The proposal to use Inconel electrodes limits the maximum glass temperature to ~1200 °C. If higher temperatures are needed for PA reasons (e.g., higher temperature, more durable glass requirements), the electrode material, and probably the design concept, will require changes. The electrode configuration proposed by Duratek for the production-scale melter is undemonstrated, although preliminary results from the SRS M-Area melter using this electrode configuration should be available before technology selection in June 1996. A replacement concept for these electrodes has not been developed and, if needed, could provide a difficult engineering challenge.

Agitation of the glass melt by means of the gas bubbler gives marked increases in throughput rates, although at the expense of increased volatility. The effectiveness and reliability of the bubbler needs to be demonstrated in extended operation, but replacement methods for failed bubblers, as opposed to electrodes, should not be difficult to engineer.

10.4.2.4 USBM. The concept of using a carbon electrode electric arc furnace for producing glass appears to have only limited commercial experience base in the production of mineral wool. However, this technology is well developed and widely used in producing metal products and fused cast ceramic refractories. The Board was impressed by the attractiveness of several operational characteristics of such a system for making a waste glass disposal product, as well as the progress made in adapting and demonstrating test systems on the LLW vitrification tasks during Phase 1 testing.

The most attractive operational characteristics for the proposed carbon electrode melter system are its apparent general robustness of construction and operation, ease of attaining high temperatures, and ease of startup and shutdown. Although the USBM WHC3 run resulted in much improvement in the fractional incorporation of volatile LLW species such as Na, K, and B, the volatility/retention issue remains for this technology. A related aspect is the need to demonstrate the ability to operate this melter system in a near-continuous operational manner with as close to a full cold-cap/feed blanket condition as can be achieved. Another unresolved issue is whether such a melter, which depends on carbon electrodes, can be operated satisfactorily using feed that contains significant levels of moisture and nitrates without excessive electrode consumption. The USBM technical staff indicated that some arc melters, in the metals industry, sheathe or coat the carbon electrodes to lessen the rates of electrode corrosion. The Board also recognized that the large size of the electrodes (>61 cm in diameter), and the need to frequently feed in electrode material because of electrode consumption during the process, may present a considerable design challenge for a remotely operated and maintained LLW vitrification facility. The USBM proposal also called for dependence on a glass skull formation, via a cooled metal containment housing for the melter, as part of extending the melter life beyond that possible for just the refractory layer itself. As with the other vendors proposing to use such a skull feature in the design, the Board was concerned about the character and long-term reliability of this condition.

10.4.2.5 WSTC. The Board believed the WSTC technology has certain positive features, for example, melt rate, scaleup simplicity, shutdown/restart/idle capability, and component modularity. However, other aspects of the technology brought out by the Phase 1 testing require extensive development that could not be accommodated within the constraints of the LLW Vitrification Program.

The high sodium borate vaporization and general uncertainty of the mass balance data are of significant concern. Glass homogeneity and general immaturity of the process suggest high risk for early implementation. The replication of 30 torch/tuyere systems could be engineered, but maintenance and remote handling will be frequent and relatively complex. Shroud gas reduction may reduce volatilization, but may potentially impact temperature control, tuyere erosion, and glass quality.

The Board concluded that it was highly unlikely that this technology could be advanced sufficiently to make it a viable option by the end of Phase 2. The Board recommended that this technology be dropped from the test program and no longer be considered.

10.4.2.6 B&W. The Board found the B&W cyclone combustion technology to be immature for LLW vitrification. This technology scored high in the areas of shutdown/restart, idling capability, upset resistance, and feed flexibility. However, the Board observed that poor results were obtained relative to volatility, offgas volume, energy consumption, tap-hole discharge failure, accumulation of material at the air inlet, atomizer/injector failure, and glass quality, giving this technology the lowest overall rating.

The key findings that led to the Board's recommendation to deselect this technology were primarily associated with offgas management systems. High volatility in the melter would require large and/or highly concentrated recycle streams. The Board had little confidence in the ability of the melter to achieve the target glass composition. The need to reduce offgas volume resulted in a complex gas treatment and recirculation system. The recommended annual inspection and repair (as needed) of the combustion chamber would be difficult in a remote environment. The Board concluded that the inability of the technology to capture feed species in the glass would result in the generation of substantial volumes of secondary waste.

The Board also concluded that it was highly unlikely that this technology could be advanced sufficiently to make it a viable option by the end of Phase 2. The Board recommended that this technology be dropped from the test program and no longer be considered.

10.5 RECOMMENDED PHASE 2 WORK

The following Phase 2 recommendations are those prepared by the Evaluation Board at the end of its evaluation deliberations conducted during May 1995. These recommendations also assume working to the original FY 1995 baseline program with a goal to select a reference LLW vitrification technology in June 1996. The recommended work scope for Phase 2 has been tailored to answer the important technical questions related to the technologies as determined by the Board. The recommended work scope was determined with the assistance of the Advisory Panel, and the advice of the cognizant engineers and other technical staff involved in evaluating other technical issues such as licensing, safety, quality assurance, mass balance and recycle, and glass quality. The decisions were reached after a careful and thorough evaluation of the vendor Phase 2 proposals, Phase 1 test results, and other pertinent information.

Phase 2 recommendations of the Board significantly curtail scope and vendor involvement as presented in the formal Phase 2 vendor proposals. Joule-based technology and carbon electrode arc/Joule melting are recommended for further study. Testing should be limited to essential needs, including some work with radioactive species, component life and reliability, electrode configuration, feed reductant tests, and detailed mass balance work under various operating conditions and chemistry. Testing should be limited to

two simulant formulations, with other parameters obtained by 'spiking.' All testing should be generic technology oriented where possible so as not to preclude vendors with equivalent technology from performing similar work.

10.5.1 Phase 2 Priorities

The Board evaluated the technical issues, Phase 2 testing objectives, and vendor capabilities, and recommended the following work scope to best meet testing objectives in a cost-effective manner. Work scope is assumed to include preparation of test plans, test reporting (as applicable), and updated technical information reports as discussed in the SOW (Wilson 1994).

The objectives of the Phase 2 work scope, as determined by the Evaluation Board, are listed below in order of priority.

- Evaluate, under radioactive conditions, the volatility behavior of Tc and Cs, and assess Re as a possible nonradioactive surrogate for Tc.
- Further evaluate material balance and volatility effects associated with slurry feeding.
- Determine the ability to maintain target glass composition with recycle of volatile components at their estimated steady-state values.
- Assess melt rate and volatility as related to bubbling rate, electrode configuration, power intensity, and cold-cap coverage of Joule-heated melters.
- Demonstrate the effectiveness of skull operation for water-cooled shell life extension.
- Investigate the impact of reductant additives on feed component volatility and on melt foaming and reboil.
- Demonstrate the performance and structural design basis of the Duratek proposed full-scale melter electrode configuration.
- Demonstrate reliability and replaceability of bubbler systems and related components.
- Evaluate a simpler moist feed preparation process compatible with carbon electrode melting and demonstrate the operability of the carbon electrode melter with moist feed.
- Evaluate graphite versus molybdenum electrodes for high-temperature Joule heating.
- Provide an engineering feasibility evaluation of Joule melter remoteability.

10.5.2 Vendor-Specific Recommendations

The Board recommended the following Phase 2 work scope for the selected vendors. Recommendations are, in general, listed in order of decreasing priority for each vendor.

10.5.2.1 Envitco.

- Perform preliminary work described in the Phase 2 proposal to include laboratory testing of feed reductant additives, EV-16 melter testing on devitrified skull, laboratory refractory testing, and required preparations for EV-5MT (5 tonne/day) testing. These tests would help to resolve feed process and refractory life issues.

- Conduct baseline testing in the EV-5MT melter for several weeks with slurry feeding based on two LLW compositions. Waste compositions based on DSSF and RI should be used adjusted for estimated recycle. Include reducible metals and Re additions in at least one of the two feed types. Include vertical top-entering electrode modification of the current EV-5MT design as part of the baseline testing. Demonstrate melter idling and offgas measurements during idling, and melter shutdown and restart. These tests would help to resolve mass balance and materials (refractory and electrode) performance concerns. Use of high- or low-convective flow mode and bubbler in baseline testing is to be determined.

- Demonstrate high- or low-convective flow melting (whichever is not in the baseline testing) using a single slurry feed type to determine the effects on mass balance and melting rate.

- Conduct mix-in-the-charger moist feed tests using a single waste type adjusted for recycle to demonstrate a simpler feed system.

- Demonstrate full cold-top operation using a dry feed such as that prepared by USBM for Phase 1 or that originally proposed for baseline testing to resolve mass balance concerns that may arise with slurry feed.

10.5.2.2 Vectra. Test plans, melter testing, and test reporting are not required during Phase 2 because melter testing is not being recommended.

- Update the full-scale melter design concept for Hanford Site LLW vitrification and describe updated concepts, including remote maintenance and operating concepts, in a Phase 2 technical information report.

- Report on Vectra's planned commercial LLW vitrification experience and lessons learned that are applicable to Hanford Site LLW vitrification issues. Also include such data as may be available through R. B. Ek and Associates and/or Oregon Steel Co. on the performance experience of, or issues with, molybdenum or carbon top-entering electrodes in the Oregon Steel Co. vitrification melters for processing electric arc furnace dust.

10.5.2.3 Duratek. The ability of Duratek to perform radioactive testing in the DM-100 enables the issue of Tc volatility and its effect on Cs volatility to be investigated as a function of redox potential and gas bubbling rate. Testing in the larger, nonradioactive DM-1000 will address the sensitivity of melting rate to gas bubbling rate to confirm the design basis melt rate.

- Perform preliminary work, as needed, to develop slurry feed reductant additions and DM-100 operating parameters to vary Fe^{+2}/Fe redox ratio from 0.0+ (atmospheric equilibration) to ~0.5 (reducing). Testing to optimize glass formulation for Phase 2 also may be included.

- Perform testing in the DM-100 using a single LLW feed type adjusted for recycle and spiked with ^{99}Tc and Re (^{237}Np also may be included). Bring the melter to a steady-state condition under oxidizing (Fe^{+2}/Fe = 0.0+) and reducing (Fe^{+2}/Fe ~0.5) and obtain data required for ^{99}Tc and Re mass balances. Use no or minimal bubbling for these tests. This radioactive testing should be given top priority to validate the use of Re as a surrogate for Tc in other Phase 2 testing. Additional tests using other redox values or a higher bubbling rate also may be carried out.

- Report on the SRS M-Area project and summarize Fernald testing results. Describe any melter upsets that may have occurred and available volatility and mass balance data (halide mass balance data for high-fluoride Fernald wastes are of particular interest).

- Perform testing in the DM-1000 using one or two waste type feeds adjusted for recycle to confirm that the DM-67K full-scale melter design basis melt rate can be achieved.

10.5.2.4 USBM. Phase 2 testing by USBM should focus on conceptualizing and demonstrating simpler feed preparation options for the electric arc melter, that is, options more suitable for remote LLW processing. Among the options that should be considered are processes such as pre-batched and blended feed that contain reductant dried in the melter or mix-in-the-charger feed.

The Board believed that WHC also should obtain the services of respective consultants or third-party companies with expert experience in (1) electric arc furnace melting, and (2) vitrification experience with related equipment or with graphite (or carbon electrode systems) to support USBM Phase 2 activities. Issues to be addressed include definition of a suitable glass pour drain, electrode protection from oxidants, remote electrode feed and maintenance design, steady-state cold-top operation with damp or wet feeds, and refinement of full-scale melter design concepts.

Testing at USBM should include the following.

- Develop simpler feed preparation methods that are compatible with large-scale remote operation for LLW processing. Conduct testing in the USBM bench-scale melter using feeds from alternative processes.

- Demonstrate steady-state cold-top melting in one or more tests in the large pilot melter system with alternatively processed feed materials.

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12.0 GLOSSARY

ABBREVIATIONS AND ACRONYMS

ASME	American Society of Mechanical Engineers
AZS	$Al_2O_3/ZrO_2/SiO_2$
B&W	Babcock & Wilcox
BD	below detectable
CELS	Corning Engineering Laboratory Services
CEM	continuous emissions monitoring
DF	decontamination factor
DOE	U.S. Department of Energy
DST	double-shell tank
DSSF	double-shell slurry feed
Duratek	GTS Duratek, Inc.
EDTA	ethylenediaminetetraacetic acid
Envitco	Envitco, Inc.
EPA	U.S. Environmental Protection Agency
Fluor	Fluor Daniel, Inc.
FY	fiscal year
HEPA	high-efficiency particulate air (filter)
HLW	high-level waste
ID	inner diameter
IFGT	integrated flue gas treatment
INEL	Idaho National Engineering Laboratory
LLW	low-level waste
N/A	not available
NARCO	North American Refractory Company
PA	performance assessment
PES	Parsons Engineering Science, Inc.
PCT	product consistency test
PEI	Penberthy Electromelt International, Inc.
PFD	process flow diagram
PNNL	Pacific Northwest National Laboratory
PODC	principal organic dangerous constituent
RI	remaining inventory
RVR	rotary volume reduction
SBS	small boiler simulator
SE	source error
SOW	Statement of Work
SpG	specific gravity
SRS	Savannah River Site
SRTC	Savannah River Technology Center
SST	single-shell tank
TCLP	toxic characteristic leaching procedure
TECO	Toledo Engineering Company
TH	Tree Hugger Corporation
THC	total hydrocarbon
TOC	total organic carbon
ton	907 kg
tonne	1,000 kg
TRU	transuranic
TWRS	Tank Waste Remediation System

USBM	U.S. Bureau of Mines
USGS	U.S. Geological Survey
Vectra	Vectra Technologies, Inc.
VSL-CUA	Vitreous State Laboratory of the Catholic University of America
Westinghouse	Westinghouse Electric Corporation
WHC	Westinghouse Hanford Company
WSTC	Westinghouse Science and Technology Center

APPENDIX A

ALTERNATIVE MELTER LOW-LEVEL WASTE PROCESS FLOW DIAGRAMS

LIST OF FIGURES

Figure A-1. Tank Waste Remediation System Combined Separations/ Low-Level Waste Treatment Facility Process Flow Diagram for Babcock & Wilcox Melter.

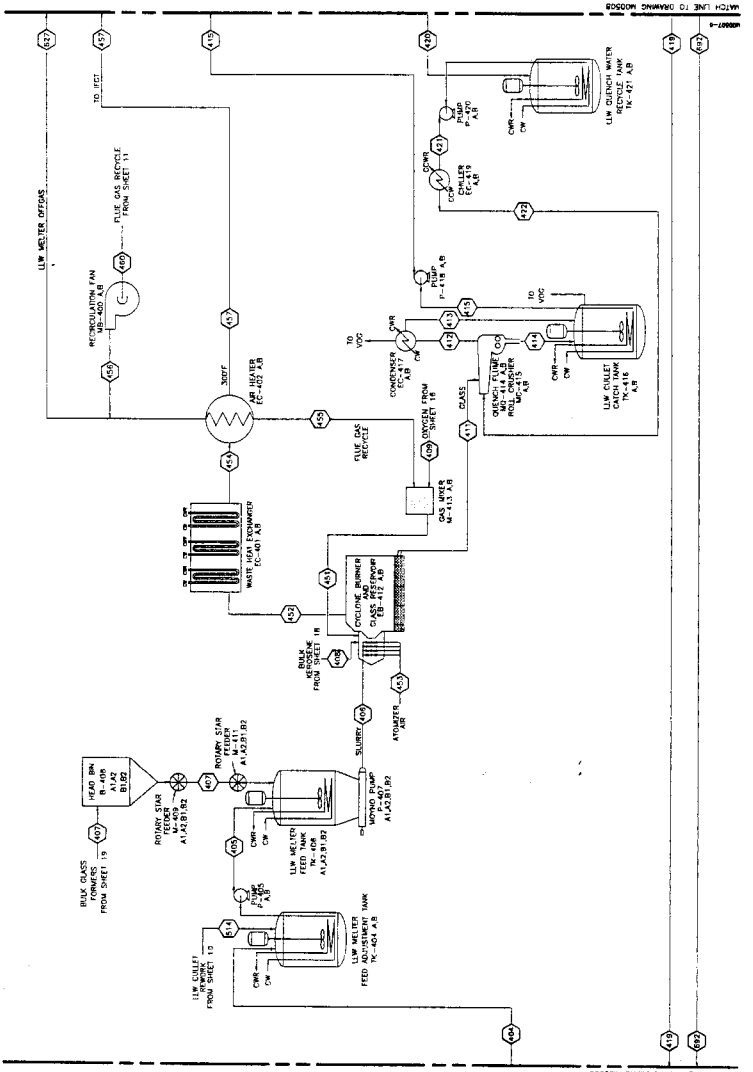


Figure A-2. Tank Waste Remediation System Combined Separations/ Low-Level Waste Treatment Facility Process Flow Diagram for Envitco, Inc. Melter with Dry Feed.

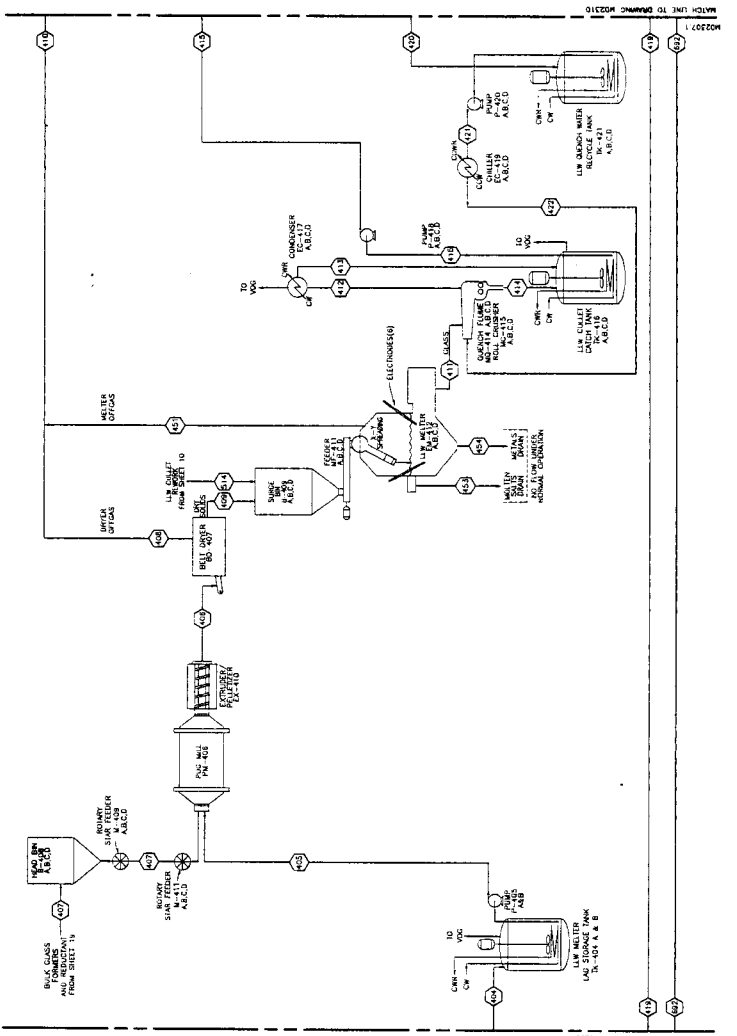


Figure A-3. Tank Waste Remediation System Combined Separations/ Low-Level Waste Treatment Facility Process Flow Diagram for Envitco Inc. Melter with Slurry Feed.

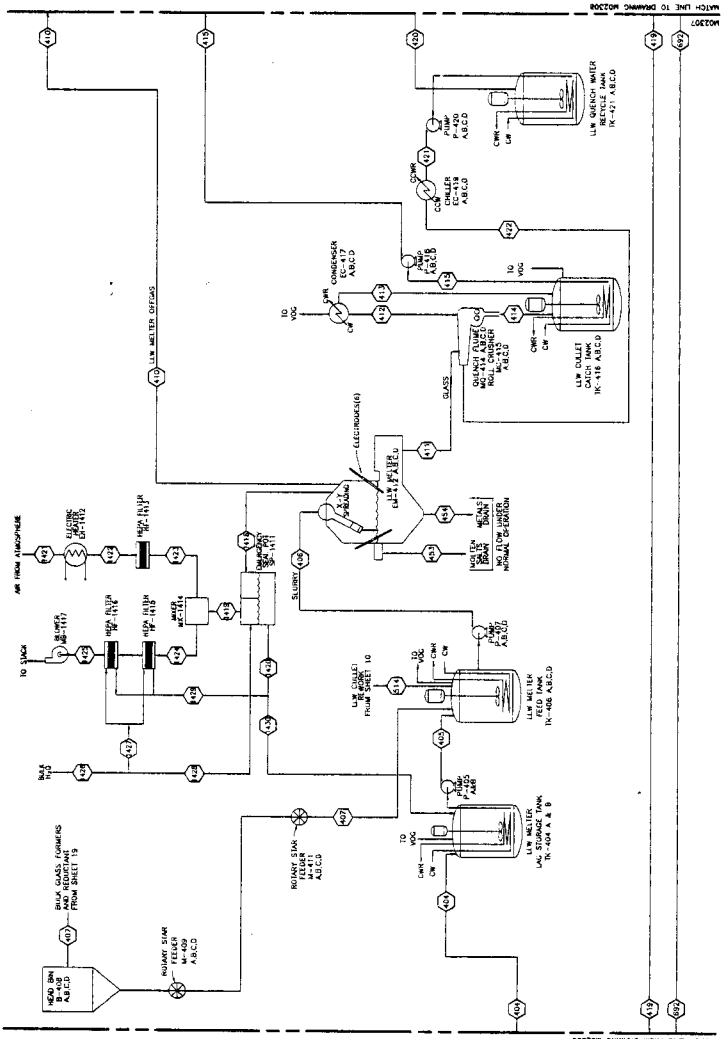


Figure A-4. Tank Waste Remediation System Combined Separations/ Low-Level Waste Treatment Facility Process Flow Diagram for GTS Duratek, Inc. Melter.

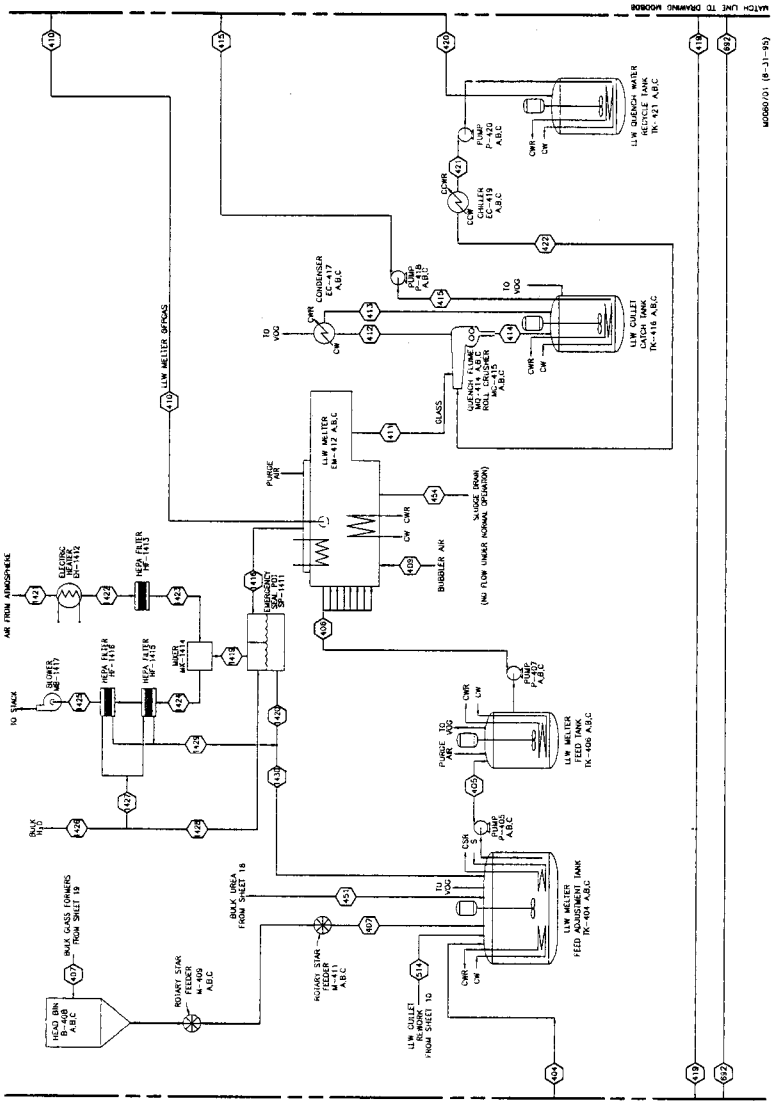


Figure A-5. Tank Waste Remediation System Combined Separations/ Low-Level Waste Treatment Facility Process Flow Diagram for Penberthy Electromelt International, Inc. Melter.

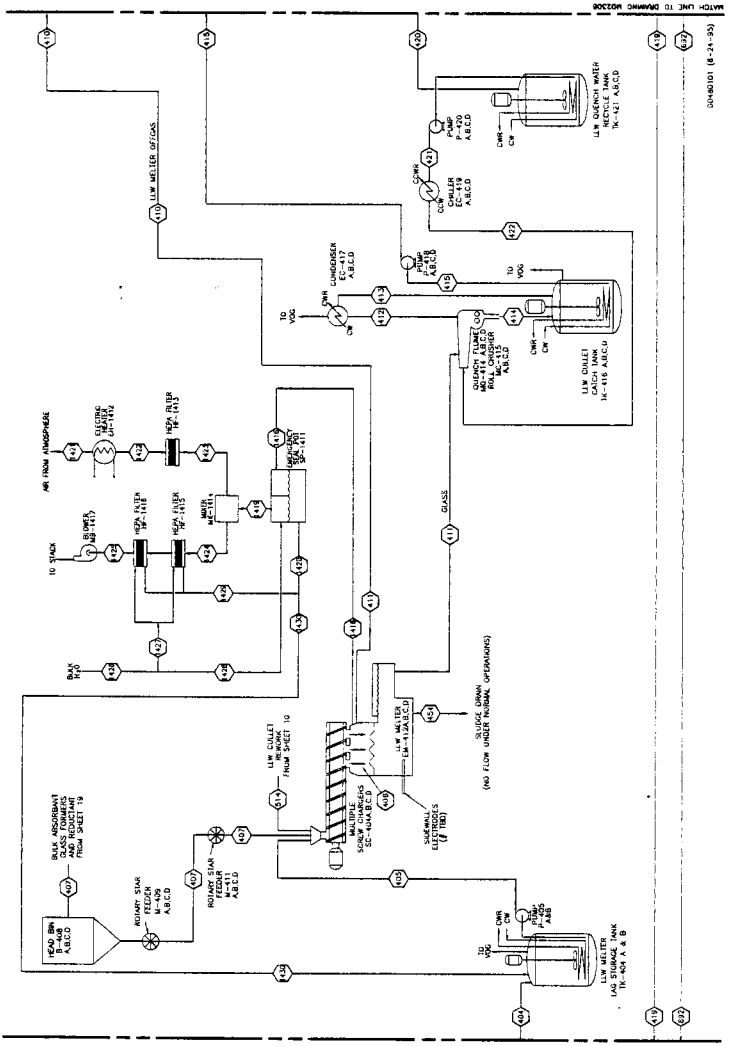


Figure A-6. Tank Waste Remediation System Combined Separations/ Low-Level Waste Treatment Facility Process Flow Diagram for U.S. Bureau of Mines Melter.

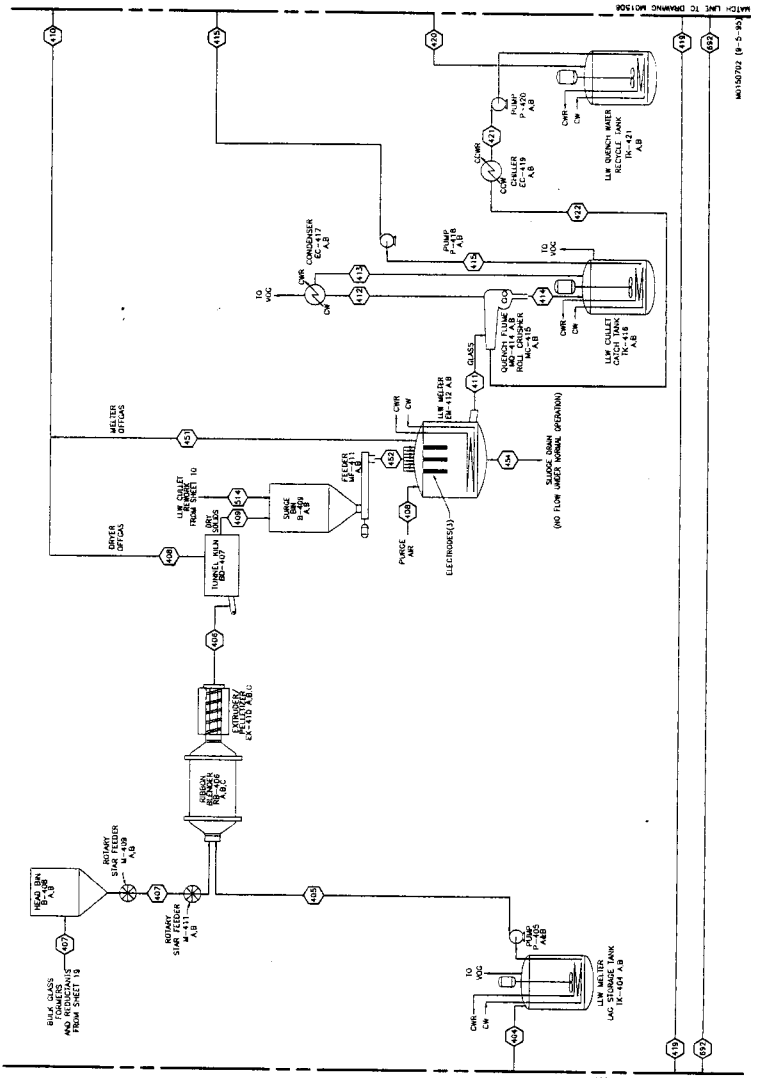


Figure A-7. Tank Waste Remediation System Combined Separations/ Low-Level Waste Treatment Facility Process Flow Diagram for Vectra Technologies, Inc. Melter with Slurry Feed.

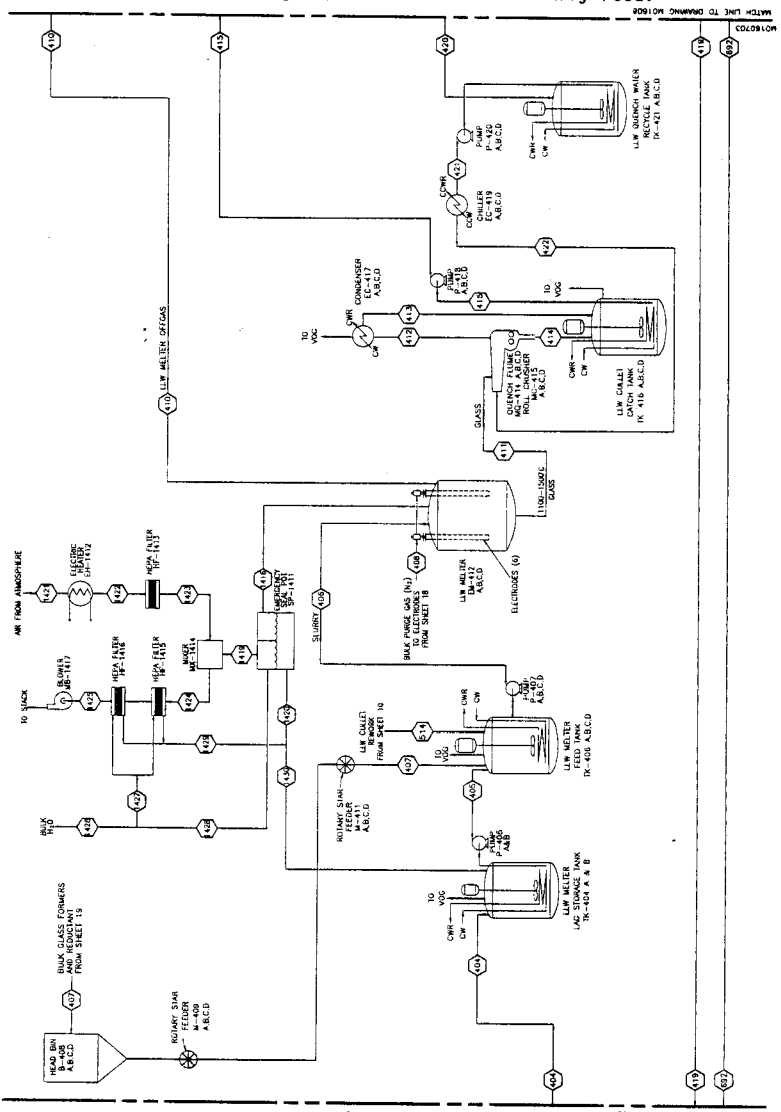


Figure A-8. Tank Waste Remediation System Combined Separations/ Low-Level Waste Treatment Facility Process Flow Diagram for Vectra Technologies, Inc. Melter with Calcined Feed.

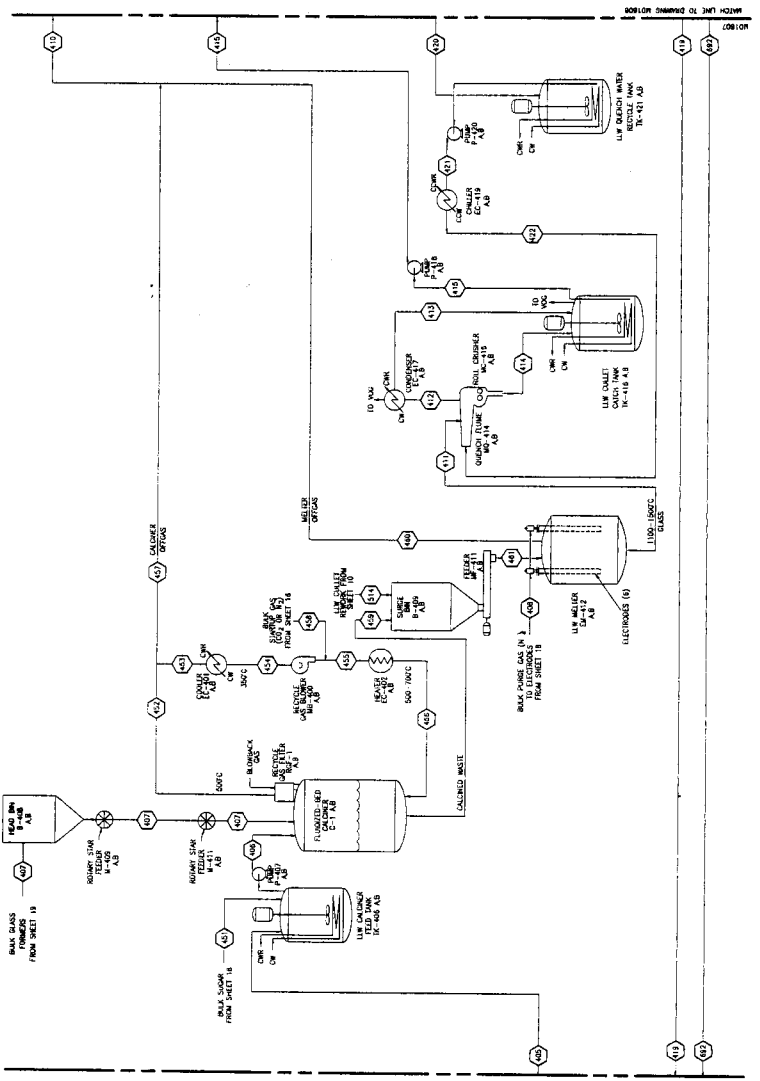
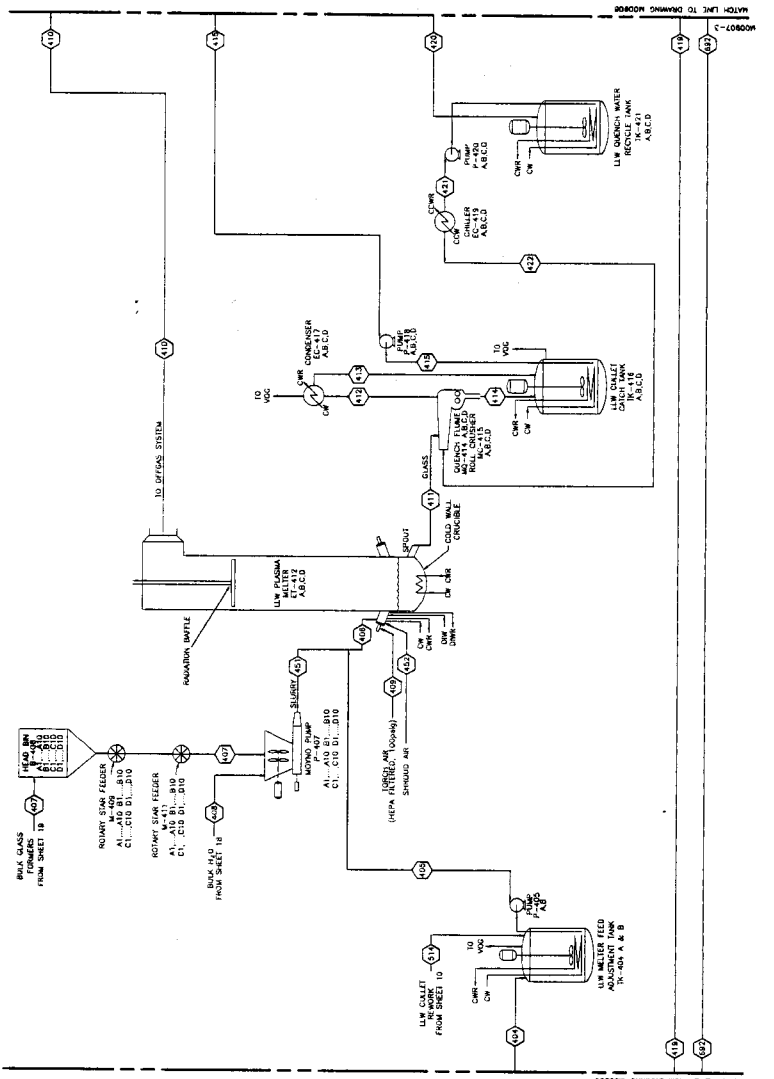


Figure A-9. Tank Waste Remediation System Combined Separations/ Low-Level Waste Treatment Facility Process Flow Diagram for Westinghouse Science and Technology Center Melter.



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APPENDIX B

FEED SYSTEM LAYOUTS

LIST OF FIGURES

LIST OF FIGURES (cont)

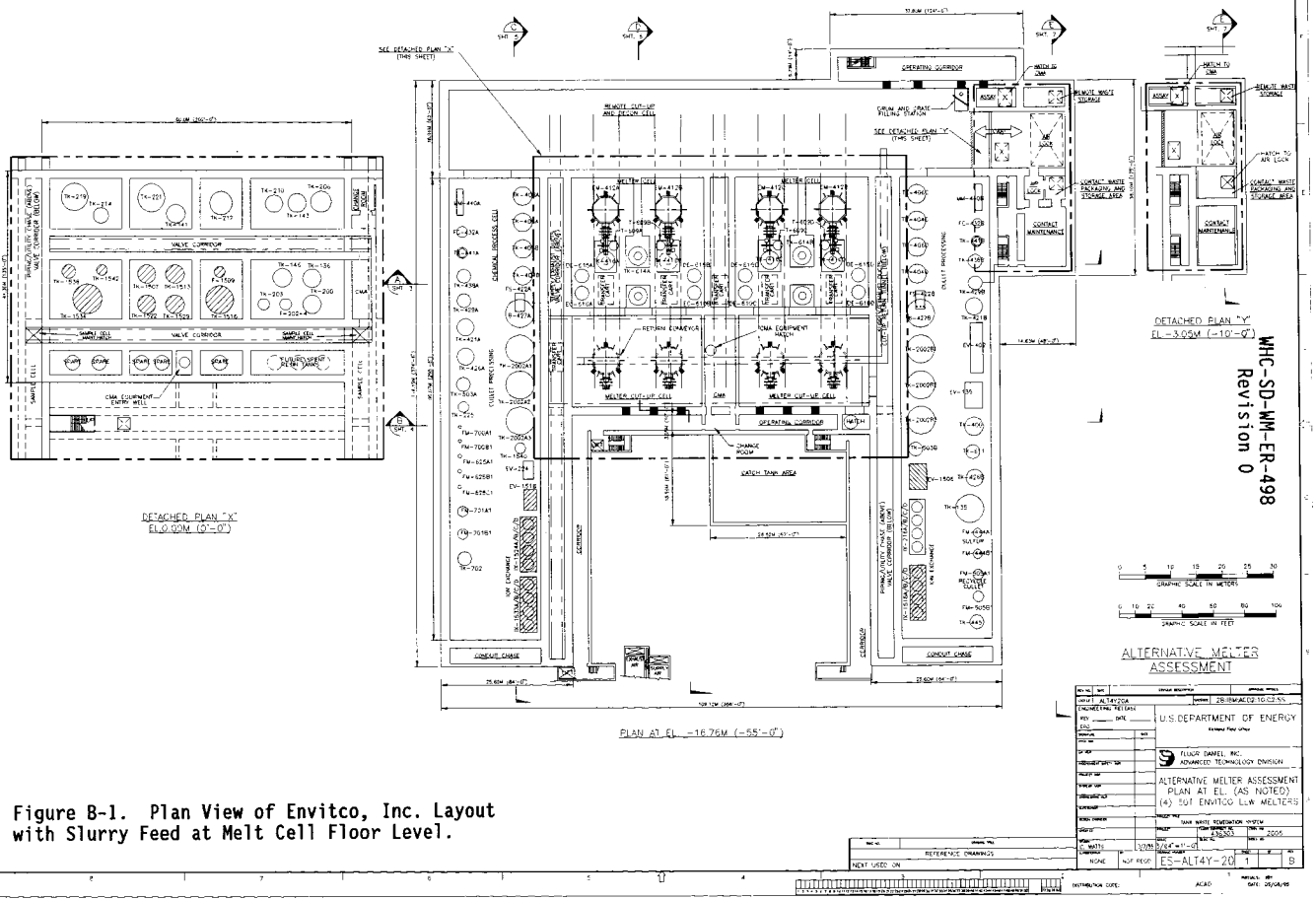
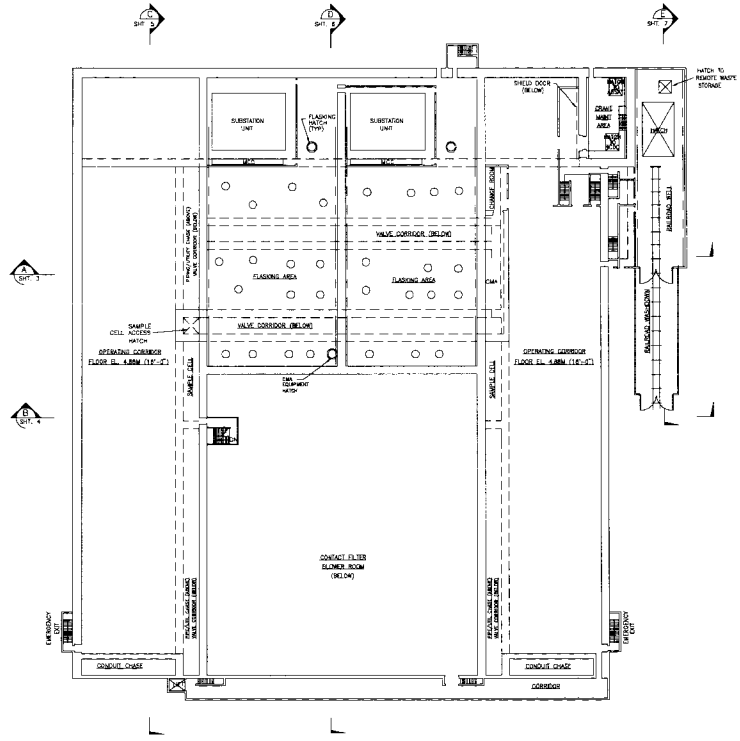


Figure B-1. Plan View of Envitco, Inc. Layout with Slurry Feed at Melt Cell Floor Level.



PLAN EL. 9.75M (32'-0") (UNLESS NOTED)

Figure B-2. Plan View of Envitco, Inc. Layout with Slurry Feed at Flasking Area Floor Level.

GRAPHIC SCALE IN METERS

GRAPHIC SCALE IN FEET

ALTERNATIVE MELTER ASSESSMENT

U.S. DEPARTMENT OF ENERGY

FLUOR DANIEL, INC. ADVANCED TECHNOLOGY DIVISION

ALTERNATIVE MELTER ASSESSMENT PLAN AT EL. 9.95M (32'-0") (4) 50T ENVITCO LLW MELTERS

TANK WASTE REMEDIATION SYSTEM

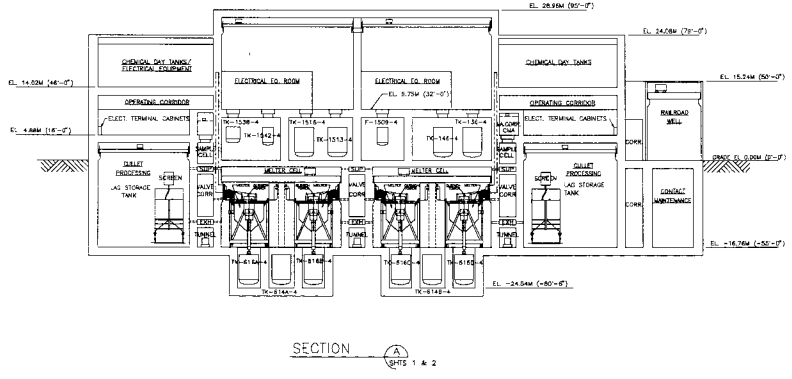
ES-ALT4Y-20 2 B

REFERENCE DRAWINGS

NEXT USED ON

NONE

NOT RELEASED



SECTION A (SHTS 1 & 2)

Figure B-3. Vertical View of Envitco, Inc. Layout with Slurry Feed Across Melt Cells, Section A.

ALTERNATIVE MELTER ASSESSMENT

GRAPHIC SCALE IN METERS

GRAPHIC SCALE IN FEET

REFERENCE DRAWINGS

NEXT USED ON

NONE

U.S. DEPARTMENT OF ENERGY
Richland Field Office

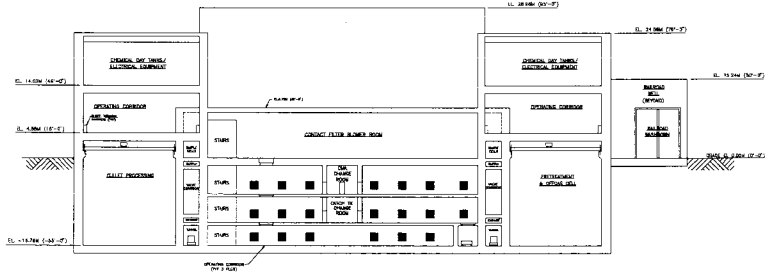
FLUOR DANIEL, INC.
ADVANCED TECHNOLOGY DIVISION

SECTION A
ALTERNATIVE MELTER ASSESSMENT
(4) 50T ENVITCO LLW MELTERS

TANK WASTE REMEDIATION SYSTEM

ES-ALT4Y-20

B-6



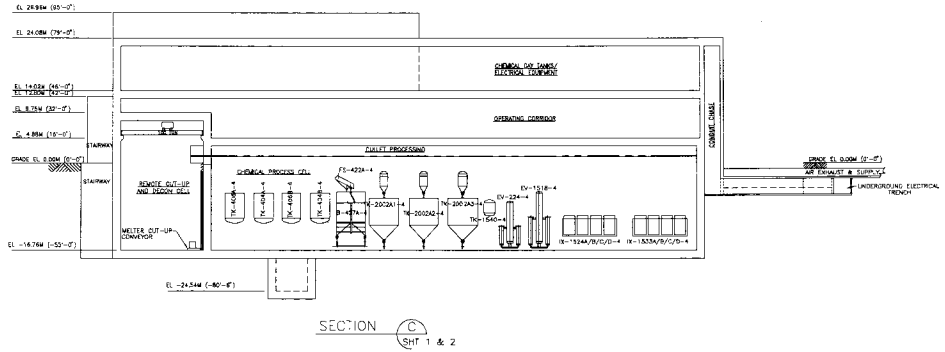
SECTION B
SHTS 1 & 2

ALTERNATIVE MELTER
ASSESSMENT

GRAPHIC SCALE IN METERS

GRAPHIC SCALE IN FEET

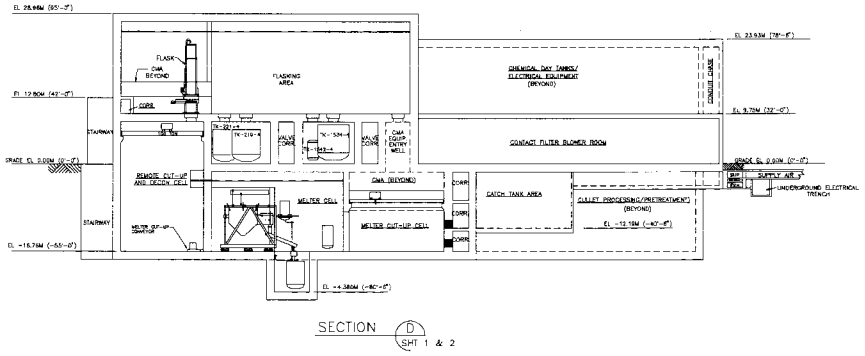
Figure B-4. Vertical View of Envitco, Inc. Layout with Slurry Feed Through Operating Corridor, Section B.



SECTION C
SHT 1 & 2

ALTERNATIVE MELTER ASSESSMENT

Figure B-5. Vertical View of Envitco, Inc. Layout with Slurry Feed Through Cullet Processing, Section C.



SECTION D
SHT 1 & 2

Figure B-6. Vertical View of Envitco, Inc. Layout with Slurry Feed Through Length of Plant at the Melter Cells, Section D.

ALTERNATIVE MELTER ASSESSMENT

U.S. DEPARTMENT OF ENERGY

FLUOR DANIEL, INC. ADVANCED TECHNOLOGY DIVISION

ALTERNATIVE MELTER ASSESSMENT SECTION D (4) SQT ENVITCO LOW MELTERS

TANK WASTE REMEDIATION SYSTEM

ES-ALT4Y-20 6 B

GRAPHIC SCALE IN METERS

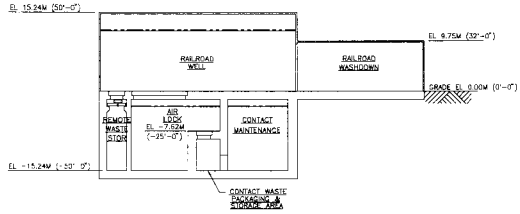
GRAPHIC SCALE IN FEET

REFERENCE DRAWINGS

NEXT USED ON

NONE NOT REQD

ACAD



ALTERNATIVE MELTER ASSESSMENT

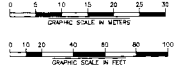
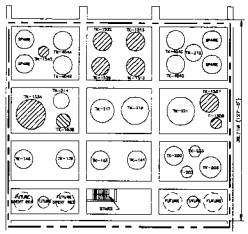
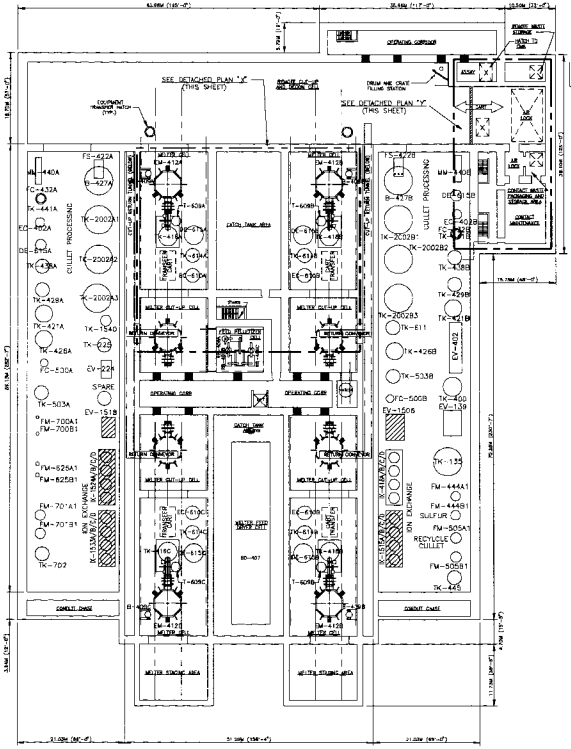


Figure B-7. Vertical View of Envitco, Inc. Layout with Slurry Feed Through Contact Maintenance Area, Section E.

U.S.DEPARTMENT OF ENERGY	
FLUOR DANIEL, INC. ADVANCED TECHNOLOGY DIVISION	
SECTION E ALTERNATIVE MELTER ASSESSMENT (4) 50T ENVITCO LLW MELTERS	
TANK WASTE REMEDIATION SYSTEM	
4/29/96	2000
E. WATTS	3/16"=1'-0"
NONE	NOT REQD
ES-ALT4Y-20	7 7
REFERENCE DRAWINGS	
NEXT USED ON	
ACAD	



DETACHED PLAN "X"
EL 0.00M (0'-0")



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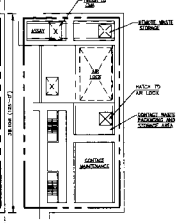

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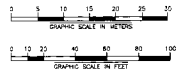
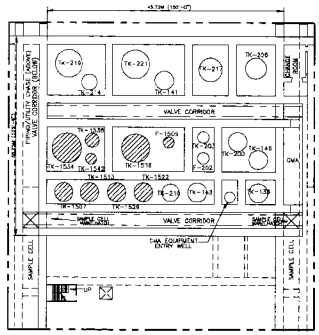
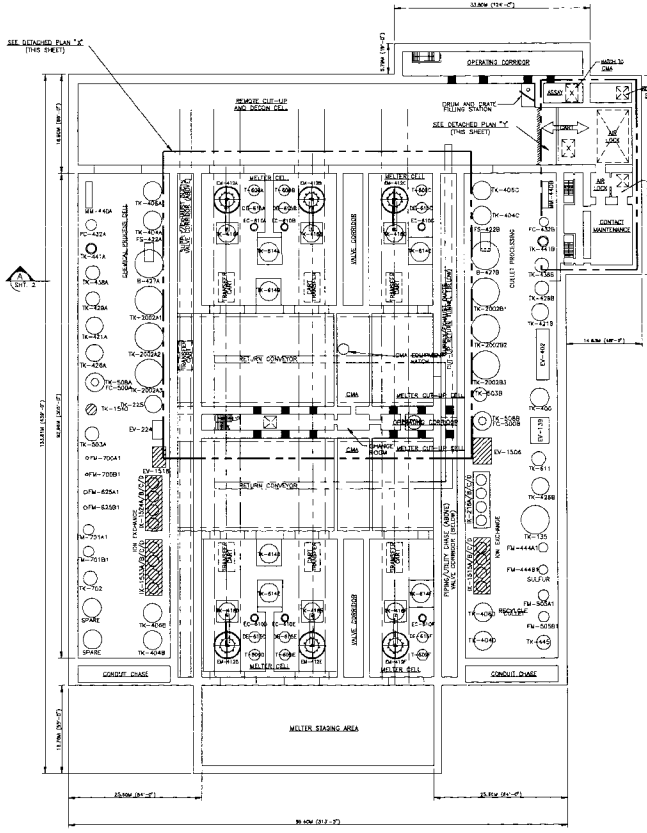


ALTERNATIVE MELTER ASSESSMENT

Figure B-8. Plan View of Envitco, Inc. Layout with Dry Feed System at the Melt Cell Floor Level.



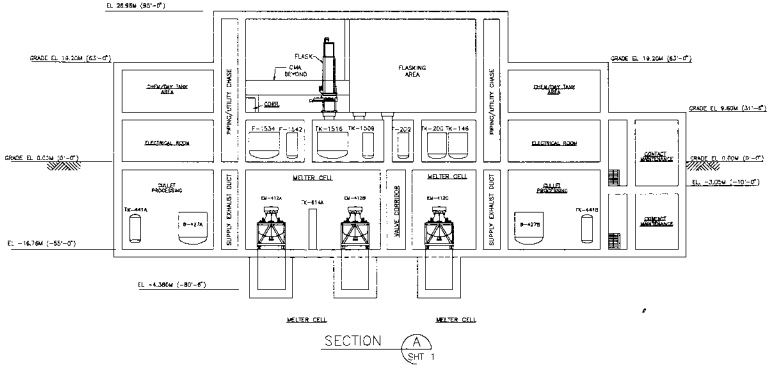
DETACHED PLAN "X"
EL.0.00M (0'-0")



DETACHED PLAN "Y"
EL.-3.05M (-10'-0")

ALTERNATIVE MELTER ASSESSMENT

Figure B-9. Plan View of Vectra Technologies, Inc. Layout at the Melt Cell Floor Level. PLAN AT EL. -15.24M (-50'-0") (UNLESS NOTED)



ALTERNATIVE MELTER ASSESSMENT

GRAPHIC SCALE IN METERS

GRAPHIC SCALE IN FEET

U.S.DEPARTMENT OF ENERGY

FLUOR DANIEL INC.
ADVANCED TECHNOLOGY DIVISION

ALTERNATIVE MELTER ASSESSMENT
SECTION A
(6) 33T VECTRA LLW MELTERS

TANK WASTE REMEDIATION SYSTEM

ES-ALT4Y-70 2 8

Figure B-10. Vertical View of Vectra Technologies, Inc. Layout Across Melt Cells, Section A.

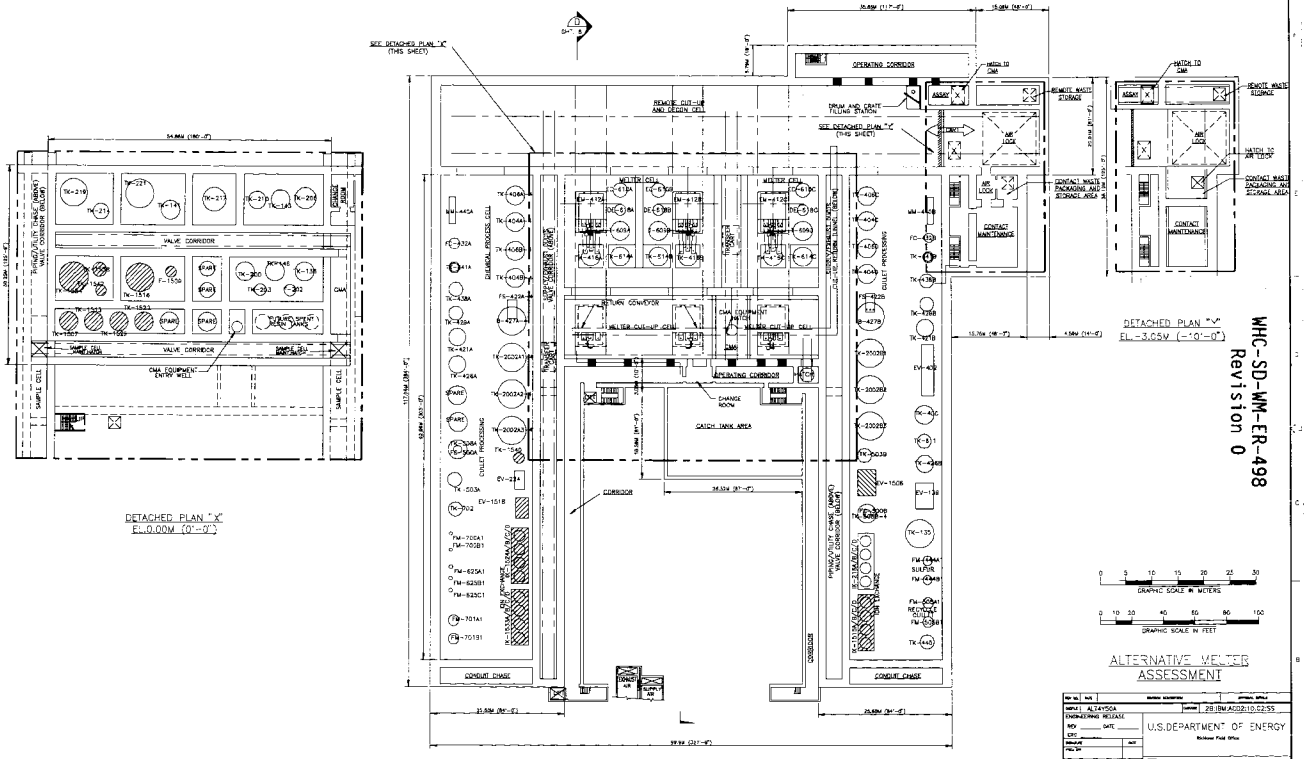
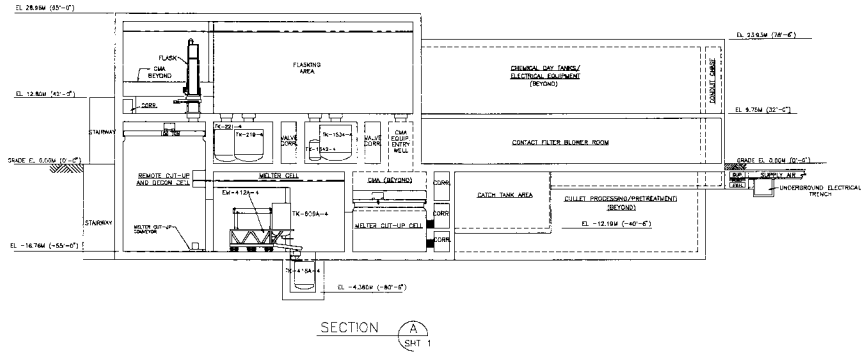


Figure B-11. Plan View of GTS Duratek, Inc. Layout at the Melt Cell Floor Level.



SECTION A
SHT 1

Figure B-12. Vertical View of GTS Duratek, Inc. Layout Through Length of Plant at the Melter Cells, Section D.

ALTERNATIVE MELTER ASSESSMENT

GRAPHIC SCALE IN METERS

GRAPHIC SCALE IN FEET

REFERENCE DRAWINGS

NEXT USED ON

U.S. DEPARTMENT OF ENERGY

FLUOR DANIEL, INC.
ADVANCED TECHNOLOGY DIVISION

ALTERNATIVE MELTER ASSESSMENT
SECTION A
(3) 67T DURATEK SLM MELTERS

TANK WASTE REMEDIATION SYSTEM

NONE

ES-ALT4Y-50 2

ACAD

B-15

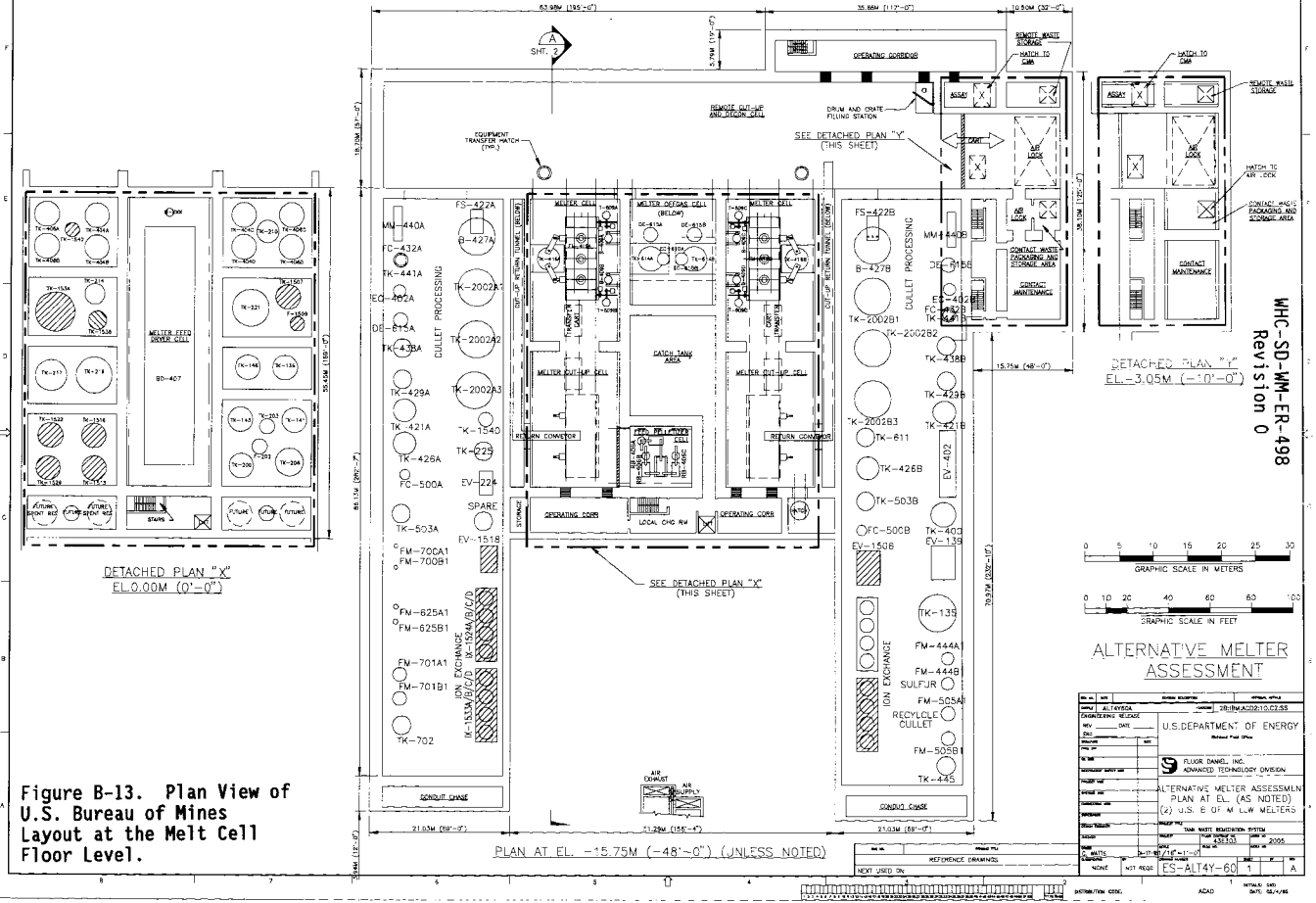
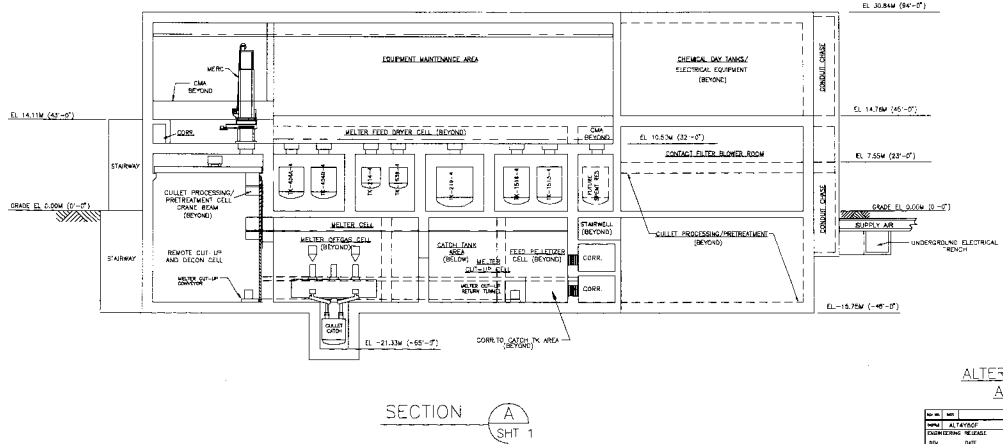
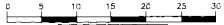


Figure B-13. Plan View of U.S. Bureau of Mines Layout at the Melt Cell Floor Level.



SECTION A
SHT 1

ALTERNATIVE MELTER ASSESSMENT



U.S.DEPARTMENT OF ENERGY
FLUOR DANIEL, INC.
ADVANCED TECHNOLOGY DIVISION
ALTERNATIVE MELTER ASSESSMENT
SECTION D
(2) 100T/D OF M LAW MELTERS
TANK WASTE REMEDIATION SYSTEM
ES-ALT4Y-60 2 A

Figure B-14. Vertical View of U.S. Bureau of Mines Layout Through Length of Plant at the Melter Cells, Section A.

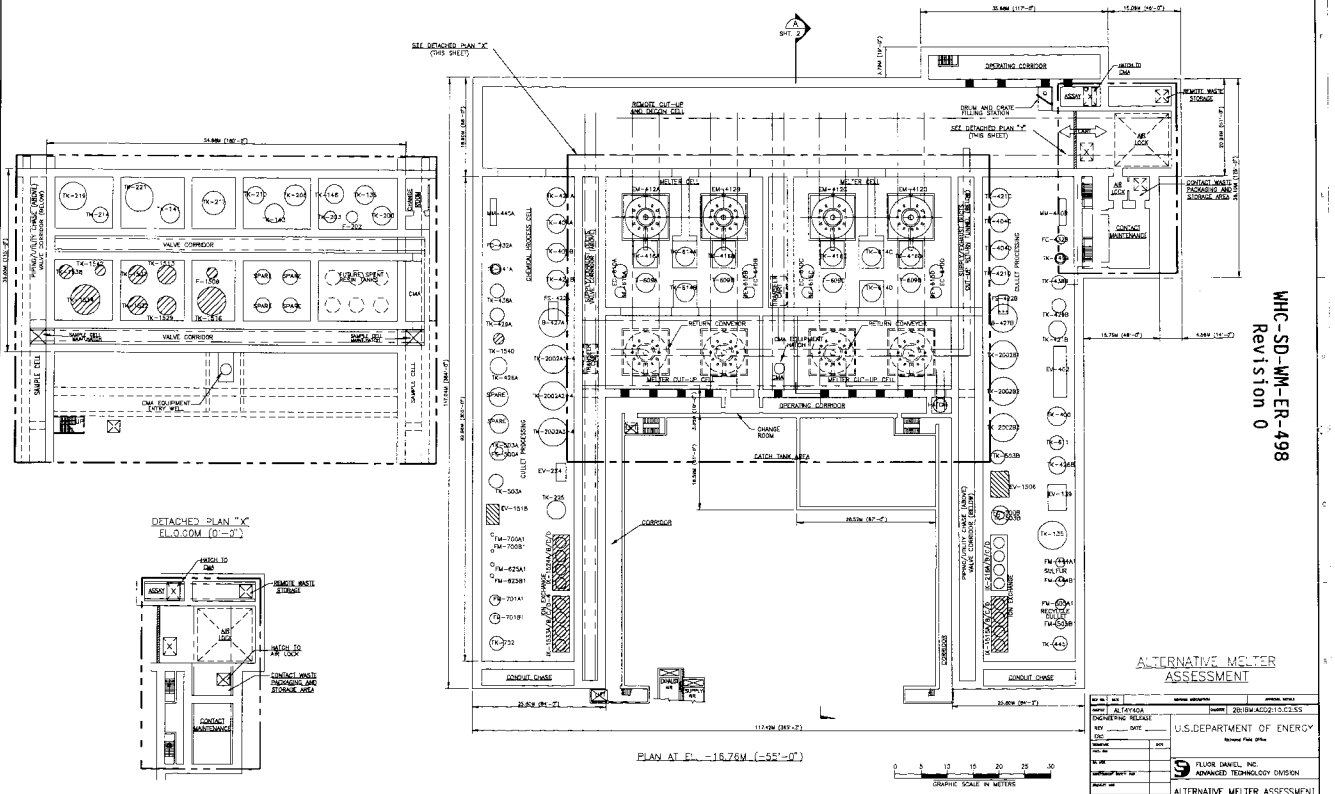
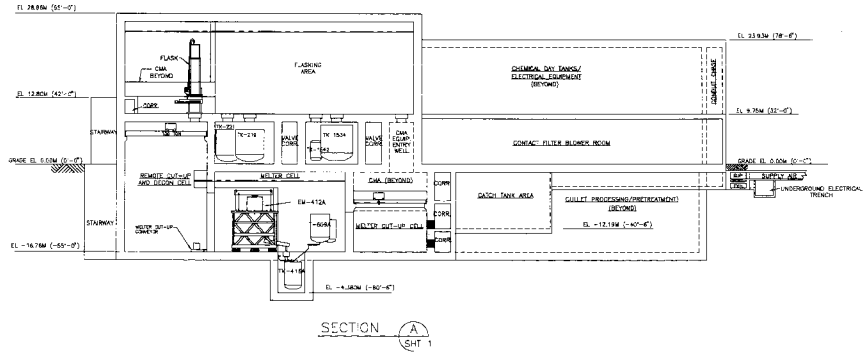


Figure B-15. Plan View of Westinghouse Science and Technology Center Layout at the Melt Cell Floor Level.



ALTERNATIVE MELTER ASSESSMENT

Figure B-16. Vertical View of Westinghouse Science and Technology Center Layout Through Length of Plant at the Melter Cells, Section A.

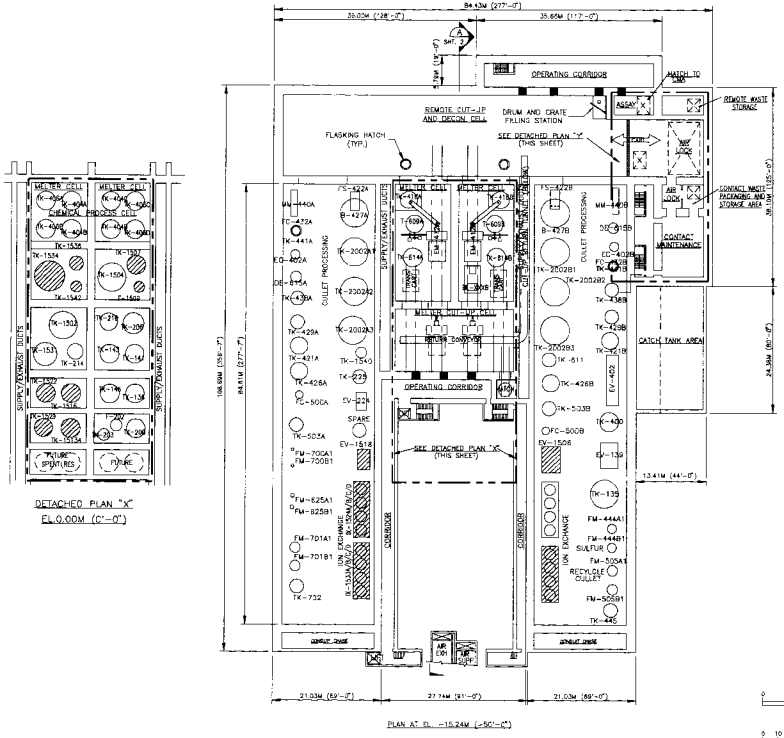
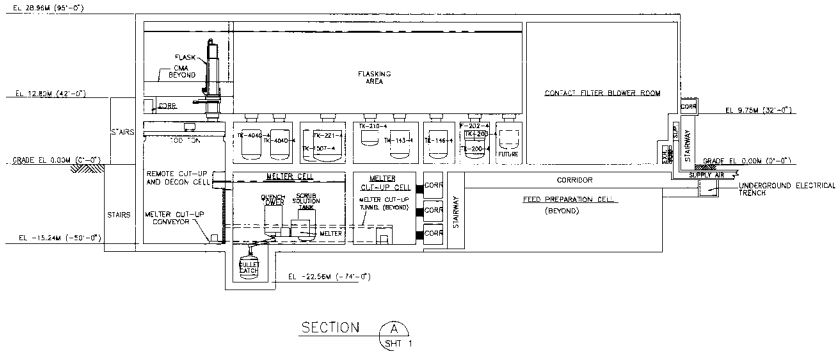
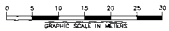


Figure B-17. Plan View of Babcock & Wilcox Layout at the Melt Cell Floor Level.



SECTION A SHT 1

ALTERNATIVE MELTER ASSESSMENT



U.S.DEPARTMENT OF ENERGY	Richland Field Office
FLUOR DANIEL, INC.	ADVANCED TECHNOLOGY DIVISION
ALTERNATIVE MELTER ASSESSMENT	SECTION A
(2) 150T B&W LLW MELTERS	
TANK WASTE REMEDIATION SYSTEM	
1/16/96 3/64"=1'-0"	
REFERENCE DRAWINGS	
NONE	ES-ALT4Y-30 2 B

Figure B-18. Vertical View of Babcock & Wilcox Layout Through Length of Plant at the Melter Cells, Section A.

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APPENDIX C

EVALUATION BOARD ADVISORY PANEL REPORT

CONTENTS

LIST OF TABLES

APPENDIX C

ADVISORY PANEL REPORT

C1.0 GENERAL

The Advisory Panel developed a process for scoring the vendor proposals as to how effective and appropriate the vendor technologies would be for the low-level waste vitrification task. This scoring system was used to rank the proposals. The Panel then offered recommendations for each vendor for Phase 2 testing programs to supply further data and information to aid in the vitrification melter selection.

C2.0 PROCESS

The Panel reviewed the vendors' proposals and heard the presentations of the cognizant engineers, then developed a list of strengths and weaknesses for each technology and a series of questions to ask each vendor.

The Panel heard the vendors' presentations and actively participated in the discussions, asking the questions prepared earlier. When all the vendors were finished, the Panel took the lead in generating a list of general technical issues and attributes judged to be of importance in selecting the best melter technology for low-level waste vitrification. These technical issues are listed in Table C-1.

A relative ranking of vendors on each technical issue was then done with 1 given to the vendor whose proposal gave the best resolution of the issue, 2 given to the next best, etc. Ties were dealt with by awarding the same number to vendors judged comparable, then skipping to a larger number, for example, two 1's were followed by a 3. This ranking is shown in Table C-2. The Panel then looked at each issue and weighted them by letters A through E as to the importance of the issue and assigned a numerical value of 10 through 2 with A being high at 10. This weighting is also shown in Table C-2.

The Panel then went back to relative ranking and gave 10 for the highest ranked vendor, looked at the lowest vendor to establish a spread, with 1 being a major spread and up to 5 being a minor spread. The ranking of the intermediate vendors was proportioned, based on the original ranking and the relative technology within the defined numerical range. The results are shown in Table C-3. The weighting factor was then multiplied by the relative rank factor to give a weighted overall score for each technical issue. These were summarized by vendor to establish vendor ranking as shown in Table C-3.

Table C-1. Technical Issues and Attributes. (2 sheets)

Number	Issue	Attributes
1	Retention/volatility	Ability for the technology to retain the major glass formers and volatile species.
2	Feed flexibility	Relates to the interest in requiring the minimum processing of liquid radioactive waste for feeding the process. There is less interest in requiring reduction of moisture content or prereaction of nitrites/nitrates.
3	Melting rate	The capability of obtaining nominal vitrification in the minimum melting unit size
4	Temperature flexibility	The ability of the melting unit to operate at higher temperatures possibly required for more durable glasses
5	Offgas temperature	Lower temperatures are desirable to limit impact of offgas system
6	Offgas volume	Lower volumes are desirable to limit impact on offgas system
7	Offgas NO_x	Lower NO_x contents are desirable to limit downstream treatment for air discharge permits
8	Energy consumption	Gauges issues relative to utility service requirements and operations lost per tonne of product.
9	Discharge flexibility	The operation and control of glass discharge related to flow control and product forms.
10	Appropriate inventory	The volume of glass in the melter relative to obtaining process stability and product consistency.
11	Life/reliability	The longevity and confidence of the unit's effective service.
12	Scaleup confidence	The confidence to ensure scaleup from size as tested or demonstrated in industrial practice relative to technical issues.
13	Maintenance/expendables	The extent to which required maintenance or replacement of system components in operation will be of concern.

Table C-1. Technical Issues and Attributes. (2 sheets)

Number	Issue	Attributes
14	Remotability	The adaptability of the process to be installed, operated, and removed from a radioactive environment.
15	Making target glass (quality)	Ability of the technology to yield a glass product matching its target composition.
16	Shutdown/restart capability	The ability of the unit to be shut down to a cold state and restarted with reasonable ease.
17	Maturity for glass making	The extent to which aspects of the technology have been proven in industrial practice and require minimal technical development for this application.
18	Secondary waste	The level to which the components can be reasonably recycled as opposed to requiring additional process steps.
19	Idle capability	The ability for the unit to operate for sustained periods without product feed, but in a production-ready state.
20	Product recycle	The capability for the unit to receive off-specification product for reprocessing.
21	Thermal stability	The unit's capability for maintaining temperature conditions necessary for product production and operational control.
22	Upset resistance	The unit's capability to maintain operational stability when exposed to potential (physical/chemical) variations in feed consistency.

Table C-2. Relative Vendor Technology Issue Rankings.

	RELATIVE VENDOR TECHNOLOGY RANKINGS						
Weight	Issue	Envitco	Vectra	Duratek	USBM	WSTC	B&W
A	Retention/Volatility	1	2	3	4	5	6
A	Maintenance/Expendables	2	3	1	4	6	5
A	Remotability	2	3	1	4	5	6
A	Maturity for glass making	1	2	1	4	5	5
B	Feed flexibility	2	2	1	6	5	4
B	Upset resistance	5	5	1	4	2	3
B	Making target glass (Quality)	1	1	3	4	5	6
B	Offgas volume	1	1	4	1	5	6
B	Life/Reliability	1	3	2	4	6	5
B	Shutdown/Restart capability	4	4	4	3	1	1
B	Idle capability	5	5	3	4	2	1
B/C	Scale-up confidence	1	4	4	3	1	6
B/C	Secondary waste	1	2	2	4	5	5
C	Temperature flexibility	3	3	5	1	2	6
C	Appropriate inventory	3	2	1	4	5	6
C	Discharge flexibility	2	5	1	4	3	6
C	Product recycle	2	2	1	4	5	5
C	Thermal stability	1	3	1	4	5	5
C/D	Melting rate	5	4	5	2	1	3
D	Energy consumption	2	2	4	1	5	6
D	Offgas temperature	1	2	3	4	5	6
E	Offgas NOx	5	1	4	3	2	6
	Number of 1s	9	3	9	3	3	2
	Number of 2s	6	8	2	1	4	0
	Number of 3s	2	5	4	3	1	2
	Number of 4s	1	3	5	14	0	1
	Number of 5s	4	3	2	0	12	6
	Number of 6s	0	0	0	1	2	11
Weight	(Multiplier)	Relative Rank Numbers					
A =	Critical (10)	1 = Relatively the best for the issue					
B =	Important (8)	2 thru 6 rankings relative to each other					
C =	Significant (6)						
D =	Minor (4)						
E =	Not Significant (2)						

Table C-3. Vendor Technical Issue Scoring.

VENDOR TECHNICAL ISSUE SCORING													
Weight		Relative Rank Factor						Scoring					
Factor	Issue	Envitco	Vectra	Duratek	USBM	WSTC	B&W	Envitco	Vectra	Duratek	USBM	WSTC	B&W
10	Retention/Volatility	10	9	7	5	2	1	100	90	70	50	20	10
10	Maintenance/Expendables	8	7	10	5	1	3	80	70	100	50	10	30
10	Remotability	9	6	10	5	4	2	90	60	100	50	40	20
10	Maturity for glass making	10	8	10	5	1	1	100	80	100	50	10	10
8	Feed flexibility	9	9	10	4	6	7	72	72	80	32	48	56
8	Upset resistance	4	4	10	6	9	8	32	32	80	48	72	64
8	Making target glass (Quality)	10	10	7	6	4	2	80	80	56	48	32	16
8	Offgas volume	10	10	8	10	6	1	80	80	64	80	48	8
8	Life/Reliability	10	7	8	6	1	2	80	56	64	48	8	16
8	Shutdown/Restart capability	2	2	2	8	10	10	16	16	16	64	80	80
8	Idle capability	2	2	7	5	8	10	16	16	56	40	64	80
8	Scale-up confidence	10	7	7	8	10	4	80	56	56	64	80	32
7	Secondary waste	10	9	9	6	2	2	70	63	63	42	14	14
6	Temperature flexibility	7	7	4	10	8	3	42	42	24	60	48	18
6	Appropriate inventory	7	8	10	6	5	4	42	48	60	36	30	24
6	Discharge flexibility	8	3	10	6	7	1	48	18	60	36	42	6
6	Product recycle	9	9	10	7	3	3	54	54	60	42	18	18
6	Thermal stability	10	8	10	7	5	5	60	48	60	42	30	30
5	Melting rate	4	5	4	7	10	6	20	25	20	35	50	30
4	Energy consumption	8	8	7	10	3	1	32	32	28	40	12	4
4	Offgas temperature	10	9	8	7	2	1	40	36	32	28	8	4
2	Offgas NOx	6	10	7	8	9	1	12	20	14	16	18	2
	Total scores							1,246	1,094	1,283	1,001	782	572
	Relative Rank Factor												
	Highest relative rank = 10 (by definition)												
	Lowest relative rank = 1 to 5 depending on spread/range of differences												
	Remainder placed proportionally within defining range (between highest and lowest)												
	Score = (weighting factor) x (relative rank factor)												

C3.0 RECOMMENDATIONS

The recommended testing programs, identified for the four remaining vendors, are considered a minimum for better identifying issues that will assist in making a Phase 3 decision. The relative importance among vendors cannot be established; they must all be pursued.

Envitco, Inc. (5 ton/day unit)

Additional testing is required to investigate a number of issues relative to a cold-cap condition using a 'wet' feed, including the following:

- Concerns with chemical attack on top-entering electrodes and holders
- Batch blanket buildup of salts or other volatile components
- The influence of various batch redox conditions on foaming/reboil
- Understanding of glass liquidus properties as they relate to a water-cooling/skull sidewall concept.

Envitco demonstrated the ability to understand the key issues and concerns the technical panel had independently identified. The panel has higher vendor confidence with Envitco as compared with Vectra Technologies, Inc. for vitrification process issues.

Vectra Technologies, Inc.

Hot glass testing will not be required for this furnace configuration.

- Vectra should study the ability to convert its configuration away from the bottom drain. A side drain is required.
- An investigation should be made of the Oregon Steel Co. commercial experience with top-entering molybdenum electrode concerns with attack by salt and its alternate experience with graphite electrodes.

GTS Duratek, Inc.

- Operate the DM-100* using some radioactive components (Cs/Tc study). A testing matrix can help quantify relative volatility as a function of temperatures and bubbling rates. This information will be relevant to all the remaining technologies, especially the interrelativity reactions between Re, Tc, and Cs, which influence volatility.
- Run tests to vary redox ratio with various reductant additives.

*DuraMelter is a trademark of GTS Duratek, Inc.

- Report on Fernald and Savannah River Site (M-Area) melter results.
- Run DM-1000 to confirm scaleup factors for 67 MT/day melter.

U.S. Bureau of Mines

- Tests must be performed to determine if this technology can use wet unreacted and/or undried feed. If not, this technology will probably be eliminated.
- The operation (with an acceptable feed) must be demonstrated to develop a 'cold cap' for better product retention of volatiles and to show consistency of operability. Feed electrical conductivity is a question.
- Confirm that the necessary recycle rate of offgas components in the feed can reach a steady-state glass composition, and demonstrate operational stability.
- Investigate commercial electric arc furnace technologies through industry vendors or consultants relative to scaleup and remotability concerns.

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APPENDIX D

SCORING BY SCORING BOARD MEMBERS

LIST OF FIGURES

LIST OF TABLES

Figure D-1. Scoring Form. (sheet 1 of 2)

PROJECT: LLW MELTER TECHNOLOGIES
TECHNOLOGY CATEGORY:_____
FIRM: _____
ADDRESS: _____
MAJOR SUBCONTRACTORS:_____
_____
_____

Name of Evaluator:_____

RATING
10 - Excellent*
8 - Good
5 - Satisfactory
2 - Poor
0 - Unsatisfactory

****

*Definitions:

Excellent — Proposal reflects exemplary fulfillment of criterion, with notable achievements demonstrated. No discernable weaknesses.
Good — Proposal fully meets criterion; any weaknesses which exist are more than offset by demonstrated strengths.
Satisfactory — Proposal appears to meet minimum requirements; weaknesses exist which are offset by strengths.
Poor — Proposal does not appear to meet minimum project requirements; major weaknesses are apparent, but can be rectified.
Unsatisfactory — Major weaknesses that cannot be rectified/tolerated.

****

A. Technical Merits of Proposed Technologies (Total 75%)

	Evaluation Criteria	Weight %		Evaluation Rating	=	Points
A.1	Maturity of the technology. Development status, including past demonstration and/or industrial applications. Do features of technology carry a high degree of technical risk? Can technical issues be resolved in a timely manner to allow definitive design to begin by November 1996? Expected cost to develop and verify the technology to the point where it can be incorporated in plant design.	0.12	X		=	
A.2	Demonstrated ability of the melter feed system and melter to reliably process projected Hanford LLW liquid/slurry feed streams (containing NaOH, $NaNO_3$, $NaNO_2$ and $NaAlO_2$ as major components; PO_4, SO_4, Cl and F; and minor components and reducible metals such as Bi, Cu, Ni, Pb and Sb as trace components) into an acceptable disposal product.	0.12	X		=	
A.3	Product quality, process control approach and the ability to produce a consistent glass product with a controlled composition.	0.08	X		=	
A.4	Design features related to operation and remote maintenance, such as the ability to drain the melter if required, ability to replace parts, and the potential for performing these operations remotely. Operational simplicity of the technology, consideration of passive design features and the amount of moving or consumable parts. Ability to maintain confinement of radioactive materials. Potential for radionuclide source buildup. Achievement of personnel exposure "as low as reasonably achievable" (ALARA) goals.	0.12	X		=	
A.5	Requirements placed on the balance of plant and support systems (e.g. facility size, compactness of design, maintenance systems, safety mitigation systems, offgas system, recycle systems and secondary waste treatment systems) by the proposed vitrification technology and process flowsheet.	0.08	X		=	
A.6	Expected operating lives for melter and radioactive contaminated support equipment and ease of disposal. Minimization of size and quantity of contaminated equipment and materials requiring disposal.	0.08	X		=	
A.7	Expected facility and operating costs. Qualitative consideration of design features and requirements (not fully considered under other criteria) that significantly affect life cycle cost, such as, initial facility cost, replacement frequency for major equipment and consumable parts, energy and utilities requirements, and requirements for expensive glass-former materials or feed additives.	0.0	X		=	
A.8	Demonstrated technical basis to scale the vitrification process to 100 metric tons/day glass production capacity.	0.07	X		=	
A.9	Flexibility to process a range of glass compositions with melting temperatures in the 1100°C to 1450°C range.	0.04	X		=	
A.10	Capability to sample product glass and capability to recycle out of specification glass.	0.04	X		=	

Figure D-1. Scoring Form. (sheet 2 of 2)

B. Phase 2 Technical Proposal (Total 10%)

	Evaluation Criteria	Weight %		Evaluation Rating		Points
B.1	Does the proposed testing address identified issues and data needs required to evaluate the technology for down selection and implementation? Are the issues, data needs, and proposed testing relevant and needed at this time?	0.02	X		=	
B.2	Capabilities of pilot/test system. Are the test systems and facilities capable of addressing testing needs (including -- sampling, instrumentation and test monitoring; feed system; offgas system; and ability to handle regulated materials). A basis must be available for scaling and adapting results of testing to the actual melter system proposed for the full scale LLW glass plant (200 TPD total plant capacity).	0.04	X		=	
B.3	Schedule. Vendors should be able to begin Phase 2 testing by September 30, 1995 and complete all Phase 2 reporting by March 1996 to support final melter selection by June 1996.	0.04	X		=	

C. Seller Qualifications (Total 15%)

	Evaluation Criteria	Weight %		Evaluation Rating		Points
C.1	Phase 1 performance, quality of Phase 1 test results and reporting. Was Phase 1 testing conducted and reporting completed on schedule in a timely manner? Were significant vendor performance problems encountered such as cost overruns, quality problems, safety, or inadequate resources?	0.03	X		=	
C.2	Understanding of technical requirements for successful operation of a vitrification facility for Hanford low-level tank wastes.	0.03	X		=	
C.3	Prior experience conducting vitrification demonstration testing and successful operating units in service.	0.03	X		=	
C.4	Qualifications of key technical staff and of subcontracted organizations, laboratories and consultants.	0.03	X		=	
C.5	Quality Assurance Program (QAP) to provide control over work judged to be consistent with good laboratory standards and practices. (see SOW section 12.0)	0.00	X		=	
C.6	Ability to provide technical support to design and construction.	0.03	X		=	

D. Cost (Total 0%)

Vendors are requested to propose a testing program broken into separable packages or options where possible. Cost estimates are to be provided for the separable options. If separable options are provided, the selection board will choose which options to be included for the purpose of cost scoring.

TOTAL SCORE

Table D-2. Evaluation Board Scoring to Selection Criteria for Vectra Technologies, Inc.

		Vectra										
Criterion	Maximum	1		2		3		4		5		Average
A.1	12	8	9.6	7	8.4	7	8.4	8	9.6	8	9.6	9.12
A.2	12	8	9.6	8	9.6	9	10.8	8	9.6	8	9.6	9.84
A.3	8	8	6.4	10	8.0	10	8.0	10	8.0	8	6.4	7.36
A.4	12	5	6.0	5	6.0	7	8.4	4	4.8	8	9.6	6.96
A.5	8	10	8.0	9	7.2	10	8.0	8	6.4	9	7.2	7.36
A.6	8	5	4.0	5	4.0	7	5.6	5	4.0	7	5.6	4.64
A.7	0							5	0.0			
A.8	7	8	5.6	7	4.9	7	4.9	5	3.5	7	4.9	4.76
A.9	4	8	3.2	9	3.6	8	3.2	10	4.0	7	2.8	3.36
A.10	4	8	3.2	8	3.2	9	3.6	2	0.8	9	3.6	2.88
A Total	75		55.6		54.9		60.9		50.7		59.3	56.28
B.1	2	2	0.4	3	0.6	5	1.0	5	1.0	4	0.8	0.76
B.2	4	2	0.8	3	1.2	8	3.2	2	0.8	5	2.0	1.60
B.3	4	2	0.8	1	0.4	8	3.2	5	2.0	5	2.0	1.68
B Total	10		2.0		2.2		7.4		3.8		4.8	4.04
C.1	3	8	2.4	10	3.0	10	3.0	5	1.5	8	2.4	2.46
C.2	3	5	1.5	7	2.1	7	2.1	8	2.4	7	2.1	2.04
C.3	3	2	0.6	1	0.3	7	2.1	8	2.4	7	2.1	1.50
C.4	3	5	1.5	8	2.4	7	2.1	9	2.7	7	2.1	2.16
C.5	0							5	0.0			
C.6	3	8	2.4	7	2.1	8	2.4	8	2.4	7	2.1	2.28
C Total	15		8.4		9.9		11.7		11.4		10.8	10.44
D	0											
Total	100		66.0		67.0		80.0		65.9		74.9	70.76

Table D-3. Evaluation Board Scoring to Selection Criteria for GTS Duratek, Inc.

		Duratek										
Criterion	Maximum	1		2		3		4		5		Average
A.1	12	8	9.6	9	10.8	10	12.0	10	12.0	10	12.0	11.28
A.2	12	8	9.6	8	9.6	7	8.4	10	12.0	7	8.4	9.60
A.3	8	8	6.4	8	6.4	7	5.6	8	6.4	9	7.2	6.40
A.4	12	8	9.6	8	9.6	10	12.0	10	12.0	10	12.0	11.04
A.5	8	10	8.0	8	6.4	8	6.4	8	6.4	9	7.2	6.88
A.6	8	8	6.4	6	4.8	8	6.4	8	6.4	8	6.4	6.08
A.7	0							5	0.0			
A.8	7	8	5.6	8	5.6	7	4.9	8	5.6	7	4.9	5.32
A.9	4	2	0.8	4	1.6	5	2.0	5	2.0	4	1.6	1.60
A.10	4	10	4.0	9	3.6	10	4.0	5	2.0	10	4.0	3.52
A Total	75		60.0		58.4		61.7		64.8		63.7	61.72
B.1	2	10	2.0	9	1.8	10	2.0	10	2.0	8	1.6	1.88
B.2	4	10	4.0	10	4.0	10	4.0	10	4.0	9	3.6	3.92
B.3	4	10	4.0	10	4.0	10	4.0	10	4.0	9	3.6	3.92
B Total	10		10.0		9.8		10.0		10.0		8.8	9.72
C.1	3	10	3.0	9	2.7	10	3.0	8	2.4	9	2.7	2.76
C.2	3	8	2.4	9	2.7	10	3.0	8	2.4	10	3.0	2.70
C.3	3	8	2.4	10	3.0	10	3.0	8	2.4	10	3.0	2.76
C.4	3	10	3.0	10	3.0	10	3.0	10	3.0	10	3.0	3.00
C.5	0							5	0.0			
C.6	3	10	3.0	9	2.7	10	3.0	8	2.4	10	3.0	2.82
C Total	15		13.8		14.1		15.0		12.6		14.7	14.04
D	0											
Total	100		83.8		82.3		86.7		87.4		87.2	85.48

Table D-4. Evaluation Board Scoring to Selection Criteria for U.S. Bureau of Mines.

		U.S. Bureau of Mines										
Criterion	Maximum	1		2		3		4		5		Average
A.1	12	5	6.0	5	6.0	5	6.0	5	6.0	5	6.0	6.00
A.2	12	5	6.0	5	6.0	5	6.0	2	2.4	5	6.0	5.28
A.3	8	5	4.0	6	4.8	6	4.8	5	4.0	6	4.8	4.48
A.4	12	5	6.0	4	4.8	5	6.0	3	3.6	5	6.0	5.28
A.5	8	5	4.0	8	6.4	10	8.0	2	1.6	8	6.4	5.28
A.6	8	5	4.0	5	4.0	6	4.8	8	6.4	6	4.8	4.80
A.7	0							5	0.0			
A.8	7	8	5.6	8	5.6	8	5.6	8	5.6	8	5.6	5.60
A.9	4	8	3.2	9	3.6	10	4.0	8	3.2	10	4.0	3.60
A.10	4	10	4.0	8	3.2	7	2.8	5	2.0	7	2.8	2.96
A Total	75		42.8		44.4		48.0		34.8		46.4	43.28
B.1	2	8	1.6	8	1.6	5	1.0	8	1.6	7	1.4	1.44
B.2	4	8	3.2	7	2.8	8	3.2	5	2.0	7	2.8	2.80
B.3	4	8	3.2	8	3.2	8	3.2	8	3.2	7	2.8	3.12
B Total	10		8.0		7.6		7.4		6.8		7.0	7.36
C.1	3	5	1.5	8	2.4	10	3.0	8	2.4	7	2.1	2.28
C.2	3	5	1.5	7	2.1	8	2.4	5	1.5	7	2.1	1.92
C.3	3	2	0.6	3	0.9	10	3.0	5	1.5	6	1.8	1.56
C.4	3	5	1.5	6	1.8	10	3.0	8	2.4	6	1.8	2.10
C.5	0							5	0.0			
C.6	3	2	0.6	4	1.2	5	1.5	2	0.6	6	1.8	1.14
C Total	15		5.7		8.4		12.9		8.4		9.6	9.00
D	0											
Total	100		56.5		60.4		68.3		50		63.0	59.64

Table D-5. Evaluation Board Scoring to Selection Criteria for Westinghouse Science and Technology Center.

	Westinghouse Science and Technology Center											
Criterion	Maximum	1		2		3		4		5		Average
A.1	12	2	2.4	2	2.4	2	2.4	1	1.2	1	1.2	1.92
A.2	12	2	2.4	2	2.4	2	2.4	2	2.4	2	2.4	2.40
A.3	8	5	4.0	2	1.6	4	3.2	5	4.0	2	1.6	2.88
A.4	12	2	2.4	3	3.6	4	4.8	3	3.6	3	3.6	3.60
A.5	8	2	1.6	5	4.0	6	4.8	0	0.0	3	2.4	2.56
A.6	8	2	1.6	3	2.4	1	0.8	2	1.6	1	0.8	1.44
A.7	0							5	0.0			
A.8	7	10	7.0	10	7.0	10	7.0	8	5.6	6	4.2	6.16
A.9	4	8	3.2	9	3.6	8	3.2	8	3.2	8	3.2	3.28
A.10	4	2	0.8	2	0.8	3	1.2	2	0.8	3	1.2	0.96
A Total	75		25.4		27.8		29.8		22.4		20.6	25.20
B.1	2	2	0.4	2	0.4	7	1.4	2	0.4	2	0.4	0.60
B.2	4	5	2.0	5	2.0	7	2.8	3	1.2	2	0.8	1.76
B.3	4	2	0.8	5	2.0	8	3.2	5	2.0	2	0.8	1.76
B Total	10		3.2		4.4		7.4		3.6		2.0	4.12
C.1	3	5	1.5	6	1.8	8	2.4	5	1.5	2	0.6	1.56
C.2	3	2	0.6	3	0.9	4	1.2	2	0.6	2	0.6	0.78
C.3	3	2	0.6	3	0.9	3	0.9	2	0.6	2	0.6	0.72
C.4	3	2	0.6	3	0.9	7	2.1	4	1.2	2	0.6	1.08
C.5	0							5	0.0			
C.6	3	2	0.6	6	1.8	4	1.2	3	0.9	2	0.6	1.02
C Total	15		3.9		6.3		7.8		4.8		3.0	5.16
D	0											
Total	100		32.5		38.5		45.0		30.8		25.6	34.48

Table D-6. Evaluation Board Scoring to Selection Criteria for Babcock & Wilcox.

		Babcock & Wilcox										
Criterion	Maximum	1		2		3		4		5		Average
A.1	12	2	2.4	1	1.2	1	1.2	0	0.0	1	1.2	1.20
A.2	12	0	0.0	2	2.4	1	1.2	2	2.4	1	1.2	1.44
A.3	8	0	0.0	2	1.6	2	1.6	0	0.0	1	0.8	0.80
A.4	12	0	0.0	1	1.2	2	2.4	0	0.0	2	2.4	1.20
A.5	8	0	0.0	2	1.6	1	0.8	0	0.0	1	0.8	0.64
A.6	8	2	1.6	2	1.6	2	1.6	2	1.6	2	1.6	1.60
A.7	0							5	0.0			
A.8	7	2	1.4	2	1.4	4	2.8	8	5.6	4	2.8	2.80
A.9	4	2	0.8	7	2.8	3	1.2	5	2.0	3	1.2	1.60
A.10	4	2	0.8	2	0.8	3	1.2	5	2.0	3	1.2	1.20
A Total	75		7.0		14.6		14.0		13.6		13.2	12.48
B.1	2	0	0.0	1	0.2	4	0.8	2	0.4	2	0.4	0.36
B.2	4	0	0.0	2	0.8	4	1.6	2	0.8	2	0.8	0.80
B.3	4	0	0.0	3	1.2	4	1.6	0	0.0	2	0.8	0.72
B Total	10		0.0		2.2		4.0		1.2		2.0	1.88
C.1	3	2	0.6	6	1.8	5	1.5	5	1.5	2	0.6	1.20
C.2	3	2	0.6	2	0.6	2	0.6	1	0.3	2	0.6	0.54
C.3	3	2	0.6	2	0.6	2	0.6	2	0.6	2	0.6	0.60
C.4	3	2	0.6	3	0.9	2	0.6	2	0.6	2	0.6	0.66
C.5	0							5	0.0			
C.6	3	2	0.6	4	1.2	8	2.4	3	0.9	2	0.6	1.14
C Total	15		3.0		5.1		5.7		3.9		3.0	4.14
D	0											
Total	100		10.0		21.9		23.7		18.7		18.2	18.50

Table D-7. Evaluation Board Scoring to Selection Criteria for Envitco, Inc.

		Envitco										
Criterion	Maximum	1		2		3		4		5		Average
A.1	12	10	12.0	10	12.0	10	12.0	10	12.0	10	12.0	12.00
A.2	12	8	9.6	9	10.8	10	12.0	8	9.6	10	12.0	10.80
A.3	8	10	8.0	10	8.0	10	8.0	10	8.0	10	8.0	8.00
A.4	12	8	9.6	8	9.6	8	9.6	5	6.0	9	10.8	9.12
A.5	8	10	8.0	9	7.2	10	8.0	8	6.4	10	8.0	7.52
A.6	8	8	6.4	7	5.6	8	6.4	5	4.0	10	8.0	6.08
A.7	0							5	0.0			
A.8	7	10	7.0	10	7.0	10	7.0	10	7.0	10	7.0	7.00
A.9	4	8	3.2	9	3.6	7	2.8	10	4.0	7	2.8	3.28
A.10	4	8	3.2	8	3.2	9	3.6	5	2.0	9	3.6	3.12
A Total	75		67.0		67.0		69.4		59.0		72.2	66.92
B.1	2	8	1.6	9	1.8	10	2.0	8	1.6	10	2.0	1.80
B.2	4	8	3.2	10	4.0	10	4.0	10	4.0	10	4.0	3.84
B.3	4	10	4.0	10	4.0	10	4.0	10	4.0	10	4.0	4.00
B Total	10		8.8		9.8		10.0		9.6		10.0	9.64
C.1	3	10	3.0	10	3.0	8	2.4	8	2.4	10	3.0	2.76
C.2	3	8	2.4	10	3.0	9	2.7	4	1.2	10	3.0	2.46
C.3	3	8	2.4	10	3.0	10	3.0	8	2.4	10	3.0	2.76
C.4	3	8	2.4	10	3.0	10	3.0	10	3.0	10	3.0	2.88
C.5	0							5	0.0			
C.6	3	10	3.0	10	3.0	10	3.0	9	2.7	10	3.0	2.94
C Total	15		13.2		15.0		14.1		11.7		15.0	13.80
D	0											
Total	100		89.0		91.8		93.5		80.3		97.2	90.36