

# Melter System Technology Testing for Hanford Site Low- Level Tank Waste Vitrification

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MELTER SYSTEM TECHNOLOGY TESTING FOR  
HANFORD SITE LOW-LEVEL TANK WASTE VITRIFICATION

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ABSTRACT

Following revisions to the Tri-Party Agreement for Hanford Site cleanup, which specified vitrification for immobilization of the low-level waste (LLW) stream to be derived from retrieval and pretreatment of the radioactive defense wastes stored in 177 underground tanks, commercially available melter technologies were tested during 1994 to 1995 as part of a multiphase program to select reference technologies for the new LLW vitrification mission. 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 were also tested. The technologies and Phase 1 testing results were evaluated and a preliminary technology down-selection and recommendations for Phase 2 testing completed. This paper describes the Phase 1 LLW melter vendor testing program and the tested technologies, and summarizes the testing results and the preliminary technology recommendations.

I. INTRODUCTION

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*,<sup>1</sup> also known as the Tri-Party Agreement. In the revised agreement, low-level waste (LLW) and high-level waste (HLW) streams generated during retrieval and pretreatment would be vitrified. The HLW vitrification plant (Hanford Waste Vitrification Plant) would be delayed and LLW vitrification initiated as the first priority. Milestones established for LLW vitrification included the following.

- 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).

An eventual plant capacity of 200 metric ton (MT) per day glass was estimated to be required to complete LLW vitrification by a target date of 2018. It was also assumed that commercially available high-capacity vitrification technology could be adapted for the LLW vitrification mission.

A two-phase melter technology testing program to be conducted with commercial vitrification technology vendors was initiated by Westinghouse Hanford Company (WHC) to comply with the Tri-Party Agreement requirements to begin melter testing with simulants by September 1994, and complete testing and select a reference melter(s) by June 1996. Phase 1 testing with seven vendors was conducted from July 1994 through May 1995. However, the Hanford Site tank waste remediation system (TWRS) privatization initiative, approved by the Secretary of Energy in September 1995, resulted in cancellation of the planned Phase 2 melter vendor testing program. The LLW melter vendor testing program and the seven vendor tech-

nologies selected for Phase 1 testing are described in this paper along with summary results and preliminary recommendations. More detailed information on the Phase 1 vendor tests and results is provided in a summary report.<sup>2</sup>

## II. LLW MELTER VENDOR TESTING PROGRAM

Objectives, testing scope, and technical requirements for the LLW melter vendor testing program are provided in the Statement of Work.<sup>3</sup> Key program features are described under the following subheadings. Demonstration tests were to be conducted by vendors in their facilities using simulated liquid LLW supplied by WHC.

### A. Objectives

The primary objective of the program was to obtain data to support the selection of generic reference technologies for Hanford Site LLW vitrification and meet the June 1996 Tri-Party Agreement milestone for this technology selection. Actual equipment suppliers would be selected in later procurements during design and construction of the LLW vitrification plant (LLWVP). 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.

Evaluations of melter feed preparation processes and melter performance were important technical objectives. Performance of the vendor's 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 important technical objectives. Specific technical objectives included the following.

- Evaluate melter feed preparation options.
- Evaluate processing throughput and efficiency of operation.
- Characterize process offgas and other effluent streams.
- Evaluate melter mass balance for volatile feed components including Na, B, Cs, Tc (Re surrogate), Cl, F, I, P, and S.
- Determine processing limits for LLW "minor components" PO<sub>4</sub>, SO<sub>4</sub>, 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 and/or shutdown and restart cycles.
- Evaluate remotability, operability, and maintainability.
- Evaluate life expectancy, reliability, and maintenance requirements.
- Evaluate scaleup from 1 to 10 MT/day systems tested to 50 to 100 MT/day.

### B. LLW Simulant

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 double-shell slurry feed (DSSF) liquid LLW stream concentrated to 10M Na concentration. Approximately 42,000 L of simulant were made up in two lots by Optima Chemicals, Inc. of Douglas, Georgia, and shipped to the melter vendors for Phase 1 testing. Target composition of the DSSF simulant on a calcined solids basis plus volatiles is given in Table 1.

### C. Glass Formulation

Glass formulation was mostly a vendor option. Two requirements placed on the glass formulation in the Statement of Work<sup>3</sup> were: (1) the waste loading (portion of the glass derived from the LLW simulant) should be approximately 25 wt%, and (2) the normalized Na release rate measured by the product consistency test (PCT) method<sup>4</sup> at 90 °C shall be less than 1 g/m<sup>2</sup>/day. Five pre-approved glass formulations developed by Pacific Northwest National Laboratory (PNNL) were offered. Vendors could choose one of the five PNNL glasses or formulate their own glass for testing. Technical support for glass formulation was made available to vendors through PNNL and Savannah River Technical Center (SRTC). Three vendors selected preapproved PNNL-developed glasses, three vendors developed their own glass formulations, and one vendor used SRTC to develop its glass formulation. Vendor-formulated glasses were also tested by PNNL for approval. The PCT durability data and melt viscosity as a function of temperature data measured on laboratory test

Table 1. Double-Shell Slurry Feed Simulant Composition on Calcined Solids Weight Basis and Volatiles.

Component	wt%
Na <sub>2</sub> O	75.22
K <sub>2</sub> O	5.71
Al <sub>2</sub> O <sub>3</sub>	12.62
CaO	0.01
Cr <sub>2</sub> O <sub>3</sub>	0.16
Cs <sub>2</sub> O	0.58
Fe <sub>2</sub> O <sub>3</sub>	0.01
MgO	0.01
MnO <sub>2</sub>	0.01
MoO <sub>3</sub>	0.59
SrO	0.43
P <sub>2</sub> O <sub>5</sub>	0.74
SO <sub>3</sub>	0.83
Cl	1.38
NaF	1.15
I	0.52
Total solids as g/L @ 10.0M Na <sup>+</sup>	412.11
Volatiles as g/100 g calcined solids	
H <sub>2</sub> O (estimated)	188
NO <sub>3</sub> <sup>-</sup>	46.6
NO <sub>2</sub> <sup>-</sup>	19.0
OH <sup>-</sup>	15.7
CO <sub>3</sub> <sup>-</sup>	3.9
Organic carbon	4.1

melts by PNNL for all the Phase 1 target glass formulations were provided to the vendors. Details on the vendor target glass formulations and characterization data from actual Phase 1 product glass samples are provided in a following paper.<sup>5</sup>

#### D. Test Monitoring, Samples, and Analyses

During testing, a variety of samples were taken by each vendor to address issues defined in the Statement of Work. Sample types included feed materials, batched melter feed, glass samples, offgas scrub and blowdown solutions, and miscellaneous deposits and residues. A WHC-developed test sample identification and chain-of-custody system was used by all seven vendors. Sample analyses were performed by WHC-contracted independent and government laboratories. Results from all analyses were sent to WHC for review and distribution to the cognizant vendors. Results from test sample analyses were also entered into an electronic database<sup>6</sup> and placed on the Hanford Local Area Network as read-only files for use by technical staff involved in technology evaluation and supporting studies. The WHC-contracted independent and government laboratories providing sample analyses were as follows:

- Quanterra Laboratories, St Louis, Missouri--Liquid samples including LLW simulant, offgas scrub solutions and blowdown solutions; chemical analyses, specific gravity, and settled solids
- Corning Laboratory Services, Corning, New York--Solid samples, feed materials, glass, miscellaneous deposits and residues; chemical analyses, microstructural analyses, phase characterization, and glass redox
- U.S. Geological Survey, Denver, Colorado--Solid samples, feed materials, glass, miscellaneous deposits and residues; chemical analyses, microstructural analyses, phase characterization, and glass redox
- WHC 222-S Laboratory--Liquid/slurry samples; specific gravity, settled and centrifuged solids content
- PNNL--Radioactive samples (from Duratek DuraMelter-100<sup>+</sup> test), duplicate analyses of selected samples analyzed at other laboratories, special and/or expedited analyses.

Offgas measurements, including continuous emissions monitoring and isokinetic particulate sampling using standard EPA methods, were performed by qualified air quality service companies that were contracted by the

melter vendors. Additional offgas measurements were also made by some of the vendors.

### III. VENDOR TECHNOLOGIES AND TESTING SUMMARIES

A request for proposal<sup>7</sup> for LLW vitrification technology demonstration was issued by WHC on February 25, 1994. Sixteen proposals were received and evaluated by a Source Evaluation Board, from which seven vendors were selected for Phase 1 demonstrations. The seven selected vendors and technologies are described below along with significant Phase 1 testing results.

#### A. Babcock & Wilcox (B&W)

Babcock & Wilcox demonstrated a slurry-fed cyclone combustion melter system at its Alliance Research Center in Alliance, Ohio. B&W vitrification technology is based on cyclone combustion technology developed for large fossil fuel-fired boilers used in the electric utility industry. Cyclone design features allow continuous tapping of slag that 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 that is attached to the wall of the main furnace cavity. When operating, a frozen glass "skull" forms on the walls of the cyclone furnace inhibiting 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. In the small boiler simulator pilot-scale system used for Phase 1 testing, the glass flowed out a bottom drain in the furnace sump into a water quench tank.

After minor startup difficulties, a 24-hour steady-state demonstration run was completed at a glass production rate of approximately 0.6 MT/day. Volatile component and offgas entrainment losses during the B&W demonstration were among the highest measured in any Phase 1 test.<sup>5</sup> B&W expects that somewhat lower volatility and entrainment losses could be achieved with equipment modifications and with larger full-scale units up to 100 MT/day capacity as proposed for the LLWVP. Significant product glass inhomogeneity suggested a need for longer refining times at glass melting temperatures. However, glass samples were sufficiently well reacted to meet the 1 g/m<sup>2</sup>/day PCT requirement. Extensive wear of the

Plibrico<sup>b</sup> 85-S refractory material lining the cyclone was observed with less wear observed on a test patch of Shamrock<sup>c</sup> 881 refractory.

#### B. Envitco, Inc. (Envitco)

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. Phase 1 testing was conducted in the Envitco EV-16 melter at Clemson University. The EV-16 melter is a small unit with a 0.45-m<sup>2</sup> melt area. The EV-16 melter is fired by four sidewall molybdenum rod electrodes and uses a proprietary mechanically controlled drain system. Envitco proposes a 50 MT/day design with slanted top-entering electrodes and overflow side drain system for the full-scale LLWVP melters.

Dry feed for Phase 1 testing was prepared from slurry at Hosokawa Bepex Corporation of Minneapolis, Minnesota, using the Bepex Unison<sup>d</sup> spray-drying process. Carbon powder was used as a reductant additive to the slurry to react with and destroy nitrate and nitrite in the LLW simulant during the drying process to reduce potential NO<sub>x</sub> emissions. The spray-dried powder was compacted and granulated to form the melter feed material. The dry feed melter demonstration was conducted over a 5-day period with full cold-top batch coverage resulting in the lowest volatile component and entrainment losses measured in any Phase 1 test. However, approximately 7 wt% water was added to the spray-dried feed before charging to the melter to control dusting and entrainment. The carbon reductant additive destroyed only about 25% of the LLW nitrate and nitrite during the spray-drying process and about one-third of the remaining nitrate and nitrite was evolved as NO<sub>x</sub> from the melter. Nominal glass melt rate during the dry feed test was about 51 kg/m<sup>2</sup>/h, or about 550 kg/day. A melt "reboil" foaming incident occurred on the last day of the dry feed demonstration after feeding a feed batch containing 10% excess carbon produced in a developmental run at Hosokawa Bepex and idling the melter at reduced power overnight.

<sup>b</sup>Plibrico is a trademark of the Plibrico Company.

<sup>c</sup>Shamrock is a trademark of the North American Refractory Company.

<sup>d</sup>Unison is a trademark of the Hosokawa Bepex Corporation.

<sup>7</sup>DuraMelter is a trademark of GTS Duratek, Inc.



Following the dry feed melter demonstration, melting with direct slurry feed was demonstrated. The slurry feed was essentially identical to the slurry that was spray dried. Correcting for incomplete cold-cap coverage achieved with single point slurry injection, melting rate achieved with slurry feed was approximately equal to that achieved with the spray-dried feed. With the exception of a melt reboil incident at the end of the dry feed run segment, and a cooling system interlock trip during the slurry feed run segment, the melter operations went smoothly.

### C. GTS Duratek, Inc. (Duratek)

Duratek of Columbia, Maryland, demonstrated a low-temperature Joule-heated melter technology using Inconel® 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 up to 67 MT/day capacity full-scale melters for the LLWVP. Duratek performed testing in its DuraMelter-100 and DuraMelter-1000 melters at Catholic University of America in Washington, D.C. The DuraMelter-100 melter is a small unit nominally rated at 100 kg/day glass while the DuraMelter-1000 melter is a larger pilot-scale melter nominally rated at 1,000 kg/day glass.

Both melters were operated during Phase 1 testing at steady-state processing rates greater than the rated 100 and 1,000 kg/day capacities. The DuraMelter-100 test melted about 600 kg of glass with an average processing rate of 61 kg/m<sup>2</sup>/h (185 kg/day) glass during the "steady-state" test segment. The DuraMelter-1000 test melted approximately 10.7 MT of glass with an average processing rate during the "steady-state" test segment of 66 kg/m<sup>2</sup>/h (1,800 kg/day) glass. Duratek used urea as a reductant additive to the slurry feed and NO<sub>x</sub> evolution measured in the DuraMelter-1000 test was about 13% based on the feed nitrate plus nitrite content. Testing in both melters went smoothly and was uneventful.

### D. Penberthy Electromelt International, Inc. (PEI)

Penberthy Electromelt International, Inc. 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. PEI melter feed system mixes the liquid LLW with absorbent glass-former additives in screw chargers that deliver

a moist granular feed directly to the melter. Multiple chargers with multiple drop points are used to maintain full batch blanket coverage and suppress volatile component losses. An advantage of the PEI "mix-in-the-charger" feed system would appear to be minimal handling and processing of radioactive feed materials. The PEI test melter had a melt area of 0.5 m<sup>2</sup> and three electrically heated drains in a lower sidewall for glass discharge. PEI proposes melters in the 25 to 50 MT/day glass capacity range for the LLWVP.

Approximately 9 hours of melter operation with mix-in-the-charger feeding were achieved. However, melter drain failures caused termination of Phase 1 testing before all testing objectives were met. Assuming feed metering and control upgrades would be made on a production system, demonstration of the mix-in-the-charger feed concept appeared to be a qualified success in that a stable full-coverage batch blanket was maintained for several hours of melter operation.

### E. U.S. Bureau of Mines (USBM)

The USBM demonstrated a carbon electrode melter at the USBM Albany Research Center in Albany, Oregon, using prereacted pelletized 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 nitrate and nitrite in LLW simulant were mostly destroyed by reaction with sugar and powdered carbon reductant additives during feed drying. USBM has proposed 100 MT/day glass capacity full-scale carbon electrode melters for the LLWVP.

Denitration in the USBM feed-drying processes was more effective than in the Bepex spray-drying process used by Envitco. During its first demonstration run, USBM produced 4.7 MT of glass during a 24-hour period. However, excessively high melting temperatures during the first run resulted in high volatile component losses. 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 a further improved drain design to allow continuous pouring of viscous glass without excessively high melting temperatures, and larger submerged carbon electrodes, it may be possible to operate the melter in a full batch coverage cold-top mode to further suppress volatile component losses. Later testing by USBM with coated

®Inconel is a trademark of Inco Alloys, Inc.

electrodes also suggested that it may be possible to operate the melter with damp unreacted feeds.

#### F. Vectra Technologies, Inc. (Vectra)

Vectra demonstrated its Ve-Skull<sup>1</sup> high-temperature Joule-heated melter with fully calcined, dried, and slurry feeds. The Ve-Skull melter is a double shell cylindrical pressure vessel with cooling water circulated between the outer and inner shells. 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 LLWVP melters and rely on a frozen glass skull layer that Vectra believes will provide extended melter life. The test melter had an effective melt area of 0.57 m<sup>2</sup>. Vectra proposes 50 MT/day slurry-fed full-scale melters of similar design for the LLWVP.

The Vectra test melter operated for 32 days during Phase 1 testing producing a total of about 10 MT of glass. The melter was operated with direct slurry feeding and dry feeding. About 500 kg 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 prereacted feed using a heated auger drying process was unsuccessful. Much of the dry feed testing was conducted with cullet, carbonate batch, or "V-Sim" simulated calcined feed. Glass melt rates achieved with slurry feed were greater than or equivalent to melt rates estimated for calcined or simulated calcine dry feeds. During the last day of the 5-day slurry feed test when offgas data were taken, glass melt rate was estimated to be about 60 kg/m<sup>2</sup>/h (820 kg/day). Glass melt rate during the 4-hour period when the Procedyne calcined material was melted is estimated at 43 kg/m<sup>2</sup>/h and glass melt rate for a simulated calcine is estimated at 57 kg/m<sup>2</sup>/h. Later "high-through-put" runs resulted in estimated glass melt rates of 67 and 62 kg/m<sup>2</sup>/h with slurry and simulated calcine feeds, respectively.

#### G. Westinghouse Science and Technology Center (WSTC)

The 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 Marc 11<sup>2</sup> plasma torch with a typical output power of 700 to 1400 kW<sub>e</sub>. WSTC used a pre-melted powdered frit as the only glass-former additive. The frit and liquid LLW simulant were fed as separate streams to a slurry pump where they were mixed and fed as a slurry to the furnace tuere between the plasma torch and the melt crucible at the bottom of the cupola.

The WSTC test produced approximately 7 MT of glass during a 24-hour demonstration run. 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.

### IV. PHASE 1 TESTING RESULTS SUMMARY

A Phase 1 summary report<sup>2</sup> provides detailed results from the Phase 1 LLW melter vendor testing and supporting engineering studies and evaluations. A few general observation and result highlights from the Phase 1 melter vendor testing are presented below.

#### A. Melter Feed Processes

Several melter feed processes were demonstrated with varied degrees of success.

1. Fluid Bed Calcination. Vectra calcined approximately 500 kg of feed in a pilot-scale fluid bed calciner. Liquid LLW with sugar as a reductant additive was fed over a fluidized bed of glass-former materials in a continuous process. Solidification and clogging of the fluid bed occurred in early trials when boric acid was included with the glass formers as a borica source. The boric acid was therefore later mixed with the calcined feed before charging to the melter. A fluid bed temperature of 500 °C and 125% stoichiometric sugar addition (based on NO<sub>3</sub>/NO<sub>2</sub> reduction to N<sub>2</sub> + CO<sub>2</sub> + H<sub>2</sub>O) were selected as optimum process parameters for the pilot production runs following several bench-scale tests. Direct charging of hot calcine from the calciner to the melter was initially proposed by Vectra for the LLWVP.

2. Prereacted Dry Feed. Three vendors demonstrated feed-drying processes where the objective was to react nitrate and nitrite with reductant additives during the drying process to reduce potential NO<sub>x</sub> emissions from the

<sup>1</sup>Ve-Skull is a trademark of Vectra Technologies, Inc.

<sup>2</sup>Marc 11 is a trademark of Westinghouse Electric Corporation.

melter. In the USBM "Type A" process, absorbent glass-former materials and carbon were pelletized and liquid LLW simulant with sugar then absorbed into the pellets. The pellets were then dried and reacted. In the "Type B" process used for most of the USBM feed, the liquid LLW simulant, sugar, and carbon and the glass-former materials were blended as a paste that was pelletized and then dried and reacted. The exothermic reaction with sugar initiated at about 200 °C and quickly proceeded to raise the temperature to about 600 °C, reacting the sugar and carbon and destroying approximately 75% to 80% of the  $\text{NO}_2/\text{NO}$ .

Vectra attempted to process dried prereacted feed in a heated auger drying system. However, this process was abandoned because of feed solidification and clogging of the hot auger drying system. Envitco spray dried a slurry of LLW simulant, powdered carbon reductant additive, and glass-former materials at approximately 200 °C, which resulted in destroying only about 25% of the  $\text{NO}_2/\text{NO}$ . The fine powdered material produced by the spray-drying process required compaction and granulation to control dusting. Additional wetting was also needed during the Envitco melter testing to control dusting and entrainment loss. The USBM Type B process appeared to be the most successful of the tested prereacted dry feed preparation processes. However, all the dry feed processes were judged to be difficult to implement in a full-scale remotely operated radioactive facility.

3. **Mix-in-the-Charger Feed.** Two vendors demonstrated variations of processes in which the liquid LLW is mixed with glass-former materials as they are continuously fed to the melter. Such systems have the advantage of minimal radioactive material processing and handling. A potential disadvantage is the need to independently meter two feed streams to ensure composition and process control. WSTC mixed powdered pre-melted frit with the liquid LLW simulant (no reductant additives) in a Moyno<sup>b</sup> pump that delivered the mixed slurry directly to the melter. PEI fed the liquid LLW simulant with dissolved sugar to screw chargers where the simulant was absorbed by a mixture of absorbing glass formers and corneal creating "damp" feed that was charged directly to the melter.

4. **Batched Slurry Feed.** Four vendors (B&W, Duratek, Envitco, and Vectra) demonstrated batched slurry feeding. In a production process, the slurry would be mixed in a batch tank and forwarded to the melter feed tank following verification of its composition. The primary difference in these processes was the reductant additives.

B&W used no reductant additive, Duratek used urea, Envitco used powdered carbon, and Vectra used sugar. Sugar appeared to be the most effective slurry feed reductant additive for reduction of  $\text{NO}_x$  emissions. No significant problems were encountered with batched slurry feeding by these four vendors.

#### B. Melt Rates

An unexpected testing result was that 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 10M Na. The fluxing action of molten Na salts in the early stages of melting is also likely beneficial. Slurry feed melt rates (glass basis) were nominally about 60  $\text{kg}/\text{m}^2/\text{h}$ , with slurry melt rates up to 67  $\text{kg}/\text{m}^2/\text{h}$  glass demonstrated by Duratek and Vectra. Glass melt rates measured with dry feeds ranged from a low of 43  $\text{kg}/\text{m}^2/\text{h}$  with the fully calcined Vectra feed to 62  $\text{kg}/\text{m}^2/\text{h}$  with Vectra simulated calcine. Higher dry feed glass melt rates ranging from 140 to 365  $\text{kg}/\text{m}^2/\text{h}$  were demonstrated by the USBM carbon electrode melter. Glass melt rate in the WSTC plasma melter was about 300  $\text{kg}/\text{h}$  with a crucible surface area of approximately 1  $\text{m}^2$ .

#### C. Melt Upsets

Three of the four Joule-heated melter vendors experienced melt foaming or reboil incidents of varied severity during Phase I testing. Use of reductant additives to destroy LLW nitrate and nitrite components (and to maintain reducing glass melts for compatibility with molybdenum electrodes), can lead to gas-liberating redox reactions in the glass melt, particularly when reductant additions and melt temperature are increased. Adequate LLW characterization and careful process control will be required to avoid such melter upsets if large Joule-heated melters are selected for the LLWVP.

#### D. Volatility and Entrainment

The lowest feed component volatility and offgas entrainment was demonstrated by Joule-heated melters with slurry feed cold cap or dry batch blanket coverage of the melt. The lowest volatility and entrainment losses were experienced with full cold-top batch coverage in the Envitco dry feed melter test. The greatest volatility and entrainment losses occurred with the B&W cyclone combustion melter. Relatively high losses also occurred in the WSTC and USBM tests. However, USBM did demon-

<sup>b</sup>Moyno is a trademark of Robbins and Meyers, Inc.

strate somewhat lower losses in later test runs. A detailed discussion of volatility and entrainment losses during Phase 1 testing is provided in the following paper.<sup>3</sup>

#### E. Glass Quality

All the vendor glass samples from Phase 1 melter testing were sufficiently well reacted to meet the <1 g/m<sup>2</sup>/day PCT Na release requirement for Phase 1 glass formulations. However, product glasses varied in homogeneity with some containing inclusions of unmelted batch components or refractory. The B&W product glass was the least homogeneous. Detailed discussions of product glass characteristics are provided in the following paper.<sup>5</sup>

### V. EVALUATION AND RECOMMENDATIONS

An Evaluation Board consisting of technical experts from the Hanford Site and the Savannah River Site, consultants from the commercial glass industry, and consultants with nuclear processing background was established to review the Phase 1 testing results and Phase 2 vendor proposals and to make recommendations for Phase 2 testing. The full Evaluation Board met in Richland, Washington, for 2 weeks during May 1995. During this time, the Board held half-day meetings with representatives from each vendor. The Board developed a list of 22 technical issues and weighting factors and rated each vendor technology against these issues. The Board also scored each vendor to pre-established selection criteria. The two scorings were consistent except for a switch between first and second place scores. Evaluation details and scoring results are provided in the Phase 1 summary report.<sup>2</sup> During the Evaluation Board deliberations, the DOE directed that the evaluation and Phase 2 recommendations be completed, but that Phase 2 testing not be started pending a decision on the TWRS privatization initiative. A summary of the Evaluation Board's recommendations is as follows.

The Board recommended that further testing of the cyclone combustion and plasma technologies not be continued into Phase 2 testing. These technologies were judged to require significant additional testing and development before full-scale implementation in the LLWVP, and it was considered unlikely that these technologies could be developed soon enough to meet the schedule requirements of the Tri-Party Agreement. A particular concern was the high volatility and entrainment losses experienced during Phase 1 testing, and the challenges implied for the design of effective offgas and secondary waste treatment systems, the recycle waste components to the melter feed, and product composition control.

Cold-top Joule-heated technologies were generally rated highest with superior melter mass balance results and maturity of technology being key considerations. The Envitico overflow side drain and Duratek airlift drain designs were preferred over the Vectra bottom drain. The Board was concerned over control of a bottom drain on a large-capacity production melter and control of the glass level within the melter so as not to expose the top-entering molybdenum electrodes to plenum gases.

Slurry feeding and mix-in-the-charger damp feeding were rated higher than dry feeding. It was concluded that the size and complexity of equipment required for the preparation of dried prereacted melter feed, and the challenges associated with operating and maintaining this equipment in a remotely operated nuclear facility, outweigh the superior melter mass balance results achieved with dry feed. The case for slurry feed was further supported by data from Phase 1 testing indicating that slurry feeding would not result in a significant melting rate penalty. Mix-in-the-charger damp feed was judged to merit further consideration as a potential process for simplifying radioactive feed processing.

Although not as mature as Joule heating for glass melting, the carbon electrode melter technology demonstrated by the USBM is a mature technology in the metals and refractories industries and was judged to be worthy of additional consideration. It was believed that incorporation of an improved drain design more suitable to continuous pouring of viscous glass may allow the melter to be operated in a continuous full-batch coverage cold-top mode further reducing volatility and entrainment losses. The USBM also believed that the melter could potentially be modified to operate with damp mix-in-the-charger feed. It was recommended that the feasibility of these modifications be demonstrated in Phase 2 testing.

The issue of <sup>99</sup>Tc volatility during LLW vitrification was recognized as a critical data need. The effects of feed reductant additives on Tc volatility and effects of Tc on Cs volatility were identified as particular data needs. Radioactive bench-scale melter testing was recommended with <sup>99</sup>Tc and Re spiked feeds with variable feed reductant additions to characterize Tc and Cs volatility as a function of melt redox conditions, and to verify Re as an adequate surrogate for Tc to allow further testing of Tc vitrification behavior in nonradioactive tests.

It was recommended that Phase 2 LLW simulant formulations be adjusted to include higher concentrations of "minor components" (PO<sub>4</sub>, SO<sub>4</sub>, Cl, F, and Cr) expected in actual LLW feeds to determine the processability limits for these components. It was also recommended

that volatile component concentrations be adjusted to include expected additions from offgas recycle. Although Phase 2 testing was canceled, the minor component issues are considered sufficiently critical that the DOE has funded fiscal year 1996 LLW melter testing at PNNL with enhanced minor component level nonradioactive feeds, some of which will also be spiked with Re as a surrogate for Tc.

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