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Final Report-Next Generation Melter Testing for High Aluminum HLW Glasses, VSL-11R2290-1

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

P.O. Box 450
Richland, Washington 99352

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Final Report

Next Generation Melter Testing for High Aluminum HLW Glasses

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for

Washington River Protection Solutions, LLC

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Completeness of Testing:

This report describes the results of work and testing specified by WRPS. The work and any associated testing followed established quality assurance requirements. The descriptions provided in this test report are an accurate account of both the conduct of the work and the data collected. Results required by the test program are reported. Also reported are any unusual or anomalous occurrences that are different from the starting hypotheses. The test results and this report have been reviewed and verified.

I. L. Pegg: I. L. Pegg **Date:** 5/18/11
VSL Program Director/Principal Investigator

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TABLE OF CONTENTS

List of Tables

List of Figures

List of Abbreviations

ADS	Air Displacement Slurry
AJHM	Advanced Joule-Heated Melter
AOD	Air Operated Diaphragm
ASME	American Society of Mechanical Engineers
CFR	Code of Federal Regulations
CUA	The Catholic University of America
DCP-AES	Direct Current Plasma Atomic Emission Spectroscopy
DF	Decontamination Factor
DM	DuraMelter®
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
FTIR	Fourier Transform Infrared Spectroscopy
HEPA	High-Efficiency Particulate Air Filter
HLW	High Level Waste
IC	Ion Chromatography
JHCM	Joule Heated Ceramic Melter
JHM	Joule-Heated Melter
LAW	Low Activity Waste
NG	Next Generation
NQA	Nuclear Quality Assurance
ORP	Office of River Protection
PNNL	Pacific Northwest National Laboratory
QARD	Quality Assurance Requirements and Description
RPP	River Protection Project
SCR	Silicon Controlled Rectifier
SIPP	Semi Integrated Pilot Plant
SRS	Savannah River Site
US	United States
VSL	Vitreous State Laboratory
WTP	Hanford Tank Waste Treatment and Immobilization Plant
WVDP	West Valley Demonstration Project
XRF	X-Ray Fluorescence Spectroscopy

SECTION 1.0
INTRODUCTION

This Final Report describes the initial DuraMelter 100 (DM100) scale testing performed to support the development of next generation advanced joule-heated melters (NG AJHMs). The initial phase of testing investigated the impacts of plenum heaters and the partial drying of melter feed prior to its introduction into the melter. The tests demonstrate the overall impacts and benefits on processing characteristics such as increases in waste processing and glass production rates, and component volatility. The results also provide melting rates for sizing calculations and compatibility of feed and off-gas treatment systems. The tests were performed with a Hanford high level waste (HLW) composition previously processed on both the DM100 melter and the HLW Pilot Melter (DM1200) [1-3]. The simulated waste containing a high concentration of aluminum was originally specified by the Office of River Protection (ORP) for testing at VSL. This waste composition is representative of high-aluminum feeds that will be processed at the Hanford Tank Waste Treatment and Immobilization Plant (WTP) and that are expected to challenge waste loading and processing rate objectives [4-6]. This works builds upon previous work performed at the Vitreous State Laboratory (VSL) of the Catholic University of America (CUA) for ORP to increase waste loadings and waste processing rates for high aluminum HLW waste streams [1-3] by glass formulation optimization, bubbling, and modest increases in melt temperature. The present tests were conducted in response to the Task Plan WP-4.1.4 [7].

The joule heated ceramic melter (JHCM) technology, as implemented at the WTP, derives from testing supported by the Department of Energy (DOE) starting in the 1970s and subsequently through selection and implementation at the West Valley Demonstration Project (WVDP) and the Defense Waste Processing Facility (DWPF). The technology utilizes a metal shell lined with high temperature refractory to contain a pool of molten glass. The temperature of the glass is maintained at around 1150ºC by joule heating the glass through submerged metallic electrodes fabricated of nickel-chromium-iron alloy (typically Inconel 690). The waste slurry is mixed with glass forming chemicals (or glass frit) in an external feed tank and then metered into the melter to establish a thin layer of feed on the surface of the glass, referred to as the cold-cap. In this cold-cap, water evaporates, feed and waste chemicals decompose, and are finally converted to glass and incorporated into the glass pool. The glass level is maintained nearly constant by periodically discharging molten glass into a canister. The rate at which waste is converted into glass determines the operating time of the vitrification facility to complete the waste treatment mission and, therefore, overall treatment costs. Over the past several years, VSL and Energy*Solutions* have developed and demonstrated various methods to improve waste processing rate through JHCMs. Some of these include:

- Melt pool bubbling
- Optimized glass formulations
- Modest increases in melter operating temperatures.

As noted above, in JHCMs, waste and glass forming chemicals or glass frit are fed onto the surface of the molten glass pool to form a cold-cap region, where a number of process rate controlling physical and chemical reactions occur. As the feed materials travel downward through the cold-cap (vertical melting process), water is evaporated, salts are decomposed and melted, and the products combine to form molten glass that becomes part of the underlying melt pool. The essential melt-rate limiting processes are the transport of heat to, and through this zone to fuel the conversion reactions and the mass transport of the reaction products away from this zone. In traditional JHCMs such as those deployed at the WVDP and DWPF in the US as well as those deployed in Germany/Belgium and Japan, the electrical energy supplied to the molten glass pool by joule heating is transported to the cold cap region through natural thermal convection, which is relatively inefficient in the viscous glass melt and, in turn, limits mass transport. In the early 1990s, VSL developed an active melt pool mixing technology that employed air sparging or "bubbling" to enhance heat and mass transport and thereby effect dramatic increases in glass production rates. This technology was licensed to Energy*Solutions* (then Duratek) for further development, demonstration and commercialization. The technology was first deployed at production scale in the Energy*Solutions* Savannah River Site (SRS) M-Area mixed waste vitrification facility and is employed in both the HLW and low active waste (LAW) melter systems at the Hanford WTP. The experience base with this technology, now includes over 11 million pounds of glass produced over many thousands of operating days on five different melter scales ranging from 0.02 m^2 melt surface area to 5 m^2 (0.02, 0.11, 1.2, 3.3, and 5 m^2), representing a demonstrated scale-up experience by a factor of 250 [1-3, 8-28] (for comparison, DWPF has a melt surface area of 2.3 m^2 and the WTP HLW and LAW melters have melt surface areas of 3.75 m^2 and 10 m^2, respectively). This experience base also spans a very wide range of waste compositions and feed types (HLW and LAW wastes high in iron, sodium, aluminum, chromium, bismuth, sulfate, etc.). An example of production rate increase with bubbling for a Hanford HLW waste is illustrated in Figure 1.1. As a result of this experience, the VSL/ES bubbler technology was selected by Savannah River Remediation for retro-fitting into the DWPF melter with the objective of doubling the melter throughput. The new bubbler system was deployed in September 2010 and has met all expectations.

Optimization of the glass formulation has been used to increase waste loading, increase glass production rate, increase retention of volatile species in the glass product, and prevent undesirable processing issues such as foaming. Initial tests with a WTP high aluminum waste stream demonstrated substantial increases in waste loading; however, production rates with aluminum and aluminum in combination with sodium limited wastes were only a third to a half of the rates obtained for bismuth, chromium, and iron limited wastes [1]. The glass formulations were subsequently revised to address these issues and tests were conducted that demonstrated increased glass production rate while retaining high waste loading and acceptable glass properties for the aluminum limited waste through the manipulation of the glass formulations and glass forming additives [2, 3].

DOE HLW treatment programs have featured joule heated ceramic melter technology for the vitrification of high level tank waste. The melter technology used at WVDP and DWPF process(ed) HLW in ceramic melters at a nominal operating temperature of 1150°C. Historically, HLW melters are operated at a nominal temperature of 1150°C to allow for sufficient temperature control for normal as well as upset conditions in an operating melter, while still

protecting the electrodes from potential damage due to unanticipated high temperature swings. Since the HLW melters deployed in the United States at WVDP and, until recently, DWPF, do not actively mix the glass pool, temperature variations within the glass pool can be relatively large (~ ±75°C) with respect to the nominal operating temperature since natural convection within the glass pool is limited in the viscous molten glass. In advancing the technology, Energy*Solutions* and VSL have demonstrated on very large scale melters (Energy*Solutions* M-Area facility, WTP HLW Pilot Melter, and the WTP LAW Pilot Melter) that active mixing of the glass pool using our patented bubbler technology significantly reduces the temperature gradient within the glass pool and allows the melter to be controlled in a tighter operating band. As a result, the operating temperature of the melter can be modestly increased to about 1175°C with the current materials of construction, (and up to 1225°C with changes of electrode and bubbler materials) while maintaining the operating integrity of the melter at the higher temperature. Tests conducted with various HLW waste streams on the DM100 and DM1200 melters have demonstrated increases in glass production rates from 0 to 225 percent while increasing the processing temperature from 1150°C to 1175°C [1-2]. Further increases in operating temperature to 1200°C and higher have been demonstrated to further increase processing rate [8, 29], which could translate into significant cost savings provided the rest of the plant can support the higher production rate. Generally, an increase in glass production rate of about one percent has been observed with increase in processing temperature of 1ºC for Hanford LAW feeds. An example of increase in processing rate with temperature is given in Figure 1.2.

Previous melter tests at the VSL have shown strong dependence of glass production rate on solids content of the feed [17]. As the solids content of the feed increases, the glass production rate increases, but at very high solids contents the rheological properties of the feed may make it difficult to handle [30, 31]. Data relating to the highest solids contents that can be accommodated by HLW feeds and the corresponding glass production rates that are achievable provide valuable information in defining the size and operating parameters of AJHMs.

Plenum heaters are used in HLW melters for various reasons such as improving processing rates or, at DWPF, to control plenum gas temperature for flammability safety reasons. In un-bubbled melters, the increase in processing rate provided by plenum heaters may be significant compared to the baseline rate, whereas in a bubbled melter the relative increase may not be high enough to warrant their inclusion [33, 34]. Again, experimental data on the effect of plenum heaters on processing rate increase for HLW feeds will be valuable in defining the size, design, and operating parameters for next generation HLW melters.

The present work involved testing with a high-aluminum glass formulation, optimized to improve waste loading and processing rate, to determine the effect of plenum heaters, high solids content, and higher operating temperature on throughput and feed processing characteristics.

1.1 Test Objectives

The principal objective of the work reported here was to evaluate the effect of plenum heaters and high solids content feed on waste processing rates for a previously tested aluminum-

limited HLW composition. The DM100-BL unit was selected for these tests since it was used previously with the HLW waste stream evaluated in this study [1-3]; it also was used for tests on HLW glass compositions [10-12], to support subsequent tests on the HLW Pilot Melter [9, 10-13], to conduct tests to determine the effect of various glass properties (viscosity and conductivity) and oxide concentrations on glass production rates with HLW feed streams [15, 16], and to assess the volatility of cesium and technetium during the vitrification of an HLW AZ-102 composition [32]. The same melter was selected for the present tests in order to maintain comparisons between the previously collected data. The melter is fitted with plenum heaters and a feed system capable of processing high solids content feed. These tests provide information on waste processing and glass production rate, melter processing characteristics, and off-gas data, including formation of secondary phases and component partitioning.

Specific objectives of these tests were the following:

- Determination of the effect of plenum heaters on glass production rate
- Determination of the effect of plenum heaters on feed processing characteristics and melter emissions
- Determination of the properties of very high solids content feeds
- Determination of the highest solids content feed that can be fed to the melter
- Determination of the increase in glass production rate with increase in feed solids content.

Plenum heaters typically provide some improvement in the processing rate of many feeds. However, the magnitude of this effect in bubbled melters is expected to be small as compared to un-bubbled melters. In the present work, tests were performed with and without plenum heaters to determine the magnitude of the effect of plenum heaters on feed processing rate to support subsequent decisions regarding the inclusion of plenum heaters in the AJHM. A major part of the energy supplied to the feed in a slurry-fed JHCM is used to evaporate water in the feed. If the solids content of the feed to the melter can be increased, improvements in feed processing rate are possible. This task was designed to investigate the potential benefits from this effect to support consideration for inclusion in the design of the AJHM.

1.2 Quality Assurance

This work was conducted under a quality assurance program that is based on NQA-1 (2004) and NQA-2a (1990) Part 2.7 that is in place at the VSL. The program is compliant with applicable criteria of 10 CFR 830.120; Office of Civilian Waste Management DOE/RW-0333P, Quality Assurance Requirements and Description (QARD) Revision 20; the American Society of Mechanical Engineers (ASME) NQA-1, 2000 and 2004; and DOE Order 414.1 C, Quality Assurance. This program is supplemented by a Quality Assurance Project Plan for WRPS work [35] that is conducted at VSL. Test and procedure requirements by which the testing activities are planned and controlled are also defined in this plan. The program is supported by VSL standard operating procedures that were used for this work [36].

1.3 DM100 Melter System

1.3.1 DM100 Feed System

A schematic diagram of the DM100 vitrification system is shown in Figure 1.3. The melter feed is introduced in batches into a feed container mounted on a load cell for weight monitoring. The feed is stirred with a variable speed mixer and constantly recirculated. Feed is normally introduced into the melter via a system designed to mimic the operation of an Air Displacement Slurry (ADS) pump, which is the present WTP baseline. The recirculation loop extends to the top of the melter where feed is diverted from the recirculation loop into the melter through a Teflon-lined feed line and water-cooled feed tube. Two mechanical timer-operated pinch valves, one on the feed line and one on the recirculation loop, are activated in a timed sequence to introduce feed into the melter at the desired rate. The feed rate is regulated by adjusting the length of each pulse, the time between each pulse, and the pressure applied to the recirculation loop. A compressed air line is attached to the feed line and can be used to automatically clear the feed line into the melter after each pulse. In the previous tests with this high aluminum waste and the current test with plenum heaters, a peristaltic pump was used in order to provide a uniform delivery of feed to the melt surface. In this system, a recirculation loop extends to the top of the melter where feed is diverted from the recirculation loop to the peristaltic pump and subsequently into the melter through a Teflon-lined feed line and water-cooled, vertical feed tube. The simulated ADS pump system was used for the tests with the high solids feed because of its better ability to handle the higher viscosity feed.

1.3.2 Melter System

Cross-sectional diagrams of the DM100-BL melter are shown in Figures 1.4.a-c. The DM100-BL unit is a ceramic refractory-lined melter fitted with five electrodes: two pairs of opposing Inconel 690 plate electrodes and a bottom electrode. Power can be supplied in either three-phase or single-phase configurations. All of the tests in the present work were performed with the upper and lower electrodes on each side connected together and powered by a single-phase supply; the bottom electrode was not powered. Melt pool agitation is achieved by either a removable lance entering from the top of the melter or a permanent bubbler installed through the bottom electrode. In these tests the lance bubbler was used. The glass product is removed from the melter by means of an airlift discharge system. The melter has a melt surface area of 0.108 m^2 and a variable glass inventory of between 110 kg, when only the bottom pair of electrodes is used, and about 170 kg when both pairs of electrodes are used, which was the case in the present tests. The melter is equipped with five silicon carbide heating elements (31” long, 1” dia., with a 16” heating zone) inserted through heater sheaths into the plenum space. The elements are heated by two circuits each powered by 50 amp 208 volt SCR’s.

1.3.3 Off-Gas System

For operational simplicity, the DM100-BL is equipped with a dry off-gas treatment system involving gas filtration operations only. Exhaust gases leave the melter plenum through a

film cooler device that minimizes the formation of solid deposits. The film-cooler air has constant flow rate and its temperature is thermostatically controlled. Consequently, under steady-state operating conditions, the exhaust gases passing through the transition line (between the melter and the first filtration device) can be sampled at constant temperature and airflow rate. The geometry of the transition line conforms to the requirements of the 40-CFR-60 air sampling techniques. Immediately downstream of the transition line are cyclonic filters followed by conventional pre-filters and HEPA filters. The temperature of the cyclonic filters is maintained above 150°C while the temperatures in the HEPAs are kept sufficiently high to prevent moisture condensation. The entire train of gas filtration operations is duplicated and each train is used alternately. An induced draft fan completes the system.

1.4 Feed Sample Analysis

Feed samples were taken directly from the feed recirculation line during each test. Feed samples were poured into a platinum/gold crucible that was placed into a programmed furnace for drying and fusion to form a glass. The glass produced from this fusion was ground to less than 200 mesh and sealed in 20-ml vials for subsequent analysis by x-ray fluorescence spectroscopy (XRF), or by acid digestion followed by direct current plasma - atomic emission spectroscopy (DCP-AES) on the resulting solution. The feed samples were also characterized for their rheological properties, density, pH, water content, and glass yield.

SECTION 2.0
WASTE SIMULANT AND BASE GLASS COMPOSITION

2.1 Waste Simulants

The waste stream compositions previously provided by DOE are given in Table 2.1 on an oxide basis [6]. The work described in the present report focused exclusively on the aluminum limited waste stream in response to the comparatively low glass production rates achieved with this waste stream in some of the earlier tests [1]. Actual Hanford HLW tank wastes are aqueous solutions with suspended solids and dissolved salts including hydroxides, nitrates, nitrites, halides, and carbonates. For the purpose of the previous [1-3] and present work, the concentrations of the volatile components (i.e., carbonate, nitrite, nitrate, and organic carbon) are assumed to be similar to those found for the AZ-102 HLW waste [14]. With the waste composition defined, formulation of the HLW waste simulant proceeds in a straightforward fashion. In general, oxides and hydroxides are used as the starting materials, with a slurry of iron (III) hydroxide (13% by weight) as one of the major constituents. Volatile inorganic components are added as the sodium salts, whereas organic carbon is added as oxalic acid. Finally, the water content was adjusted to target a glass yield of 500 g of glass per liter of feed. The composition of the waste simulant using aluminum hydroxide as the source of aluminum and formulated to produce 100 kg of waste oxides is given in Table 2.2.

2.2 HWI-Al-19 Glass

The HWI-Al-19 glass formulation for the ORP-provided high aluminum waste composition [2] was developed and tested on both the DM100 and DM1200 melters to determine processing rates [2, 3]. These tests demonstrated that the formulation exceeded WTP requirements with respect to glass production rate and processed at a faster rate than the previous formulation (HLW-E-Al-27 [1]) developed for the same waste, while maintaining a 45 wt% waste loading.

The composition and properties of the HWI-Al-19 formulation are listed in Table 2.3 and the melter feed composition with $Al(OH)_3$ as the aluminum source is shown in Table 2.4. Based on the results from small-scale melt rate testing, the formulation emphasized increased boron concentrations to improve melt rates and compensating changes to maintain other glass properties within acceptable ranges. The additional constituents required to form the target test glass from the HLW high aluminum waste simulant are boron, calcium, lithium, sodium, and silicon. The corresponding chemical additives that are the sources for these elements were selected based on previous testing and the current baseline chemicals for the WTP Project. The measured viscosity and conductivity of HWI-Al-19 at 1150°C are 33 P and 0.27 S/cm, respectively. No crystalline phases were observed in the as-melted sample, while heat treatment for 72 hours at 950°C resulted in 1.3 vol% of Fe-rich spinel crystals. Chemical durability was

verified on crucible and melter glasses, which produced leachate concentrations well below acceptable limits [2].

2.3 Melter Feed Formulation

Melter feeds were produced by NOAH Technologies Corporation, the supplier of simulant and feed samples used in previous testing on the DM100 and DM1200 melter systems. The feed as received at VSL contained 49 weight percent water. For the test targeting the nominal feed solids content (500 g glass per liter), water was added resulting in feed containing 57 weight percent water. For the dried feed test, the drummed feed received from NOAH was heated externally with band heaters to evaporate water, thereby reducing the water content to 34 weight percent. This level of moisture resulted in no free standing water on the surface of the feed and was judged to be the minimum water content at which the feed could be effectively stirred.

Samples of the melter feed used for these tests, as well as samples at intermediate water contents, were subjected to rheological characterization. The results from rheological characterization of a variety of other melter feeds and waste simulants, as well as the effects of a range of test variables, are described in detail in a separate report [30]. Melter feeds were characterized using a Haake RS75 rheometer, which was equipped with either a Z40DIN or a FL22-SZ40 sensor. A typical set of measurements consists of identifying the flow characteristics of the slurry by measuring the shear stress on the slurry at controlled shear rates and temperatures. In these measurements, the shear rate values are preset and are increased stepwise from 0.01 s^{-1} to 200 s^{-1} (70 s^{-1} for FL22-SZ40) with a sufficient delay (typically 15 to 30 seconds) between steps to ensure that the shear stress is allowed to fully relax and therefore is measured at equilibrium. This approach is somewhat different from the "flow curve" approach in which the shear rate is ramped up to some maximum value and then ramped back down to produce a hysteresis curve that is dependent on the selected ramp rate. The viscosity of the sample as a function of the shear rate is then calculated as the ratio of the shear stress to the shear rate. The yield stress data for the melter feeds were measured using a controlled-stress mode in which the torque on the rotor was slowly increased while the resulting deformation of the fluid was monitored. The discontinuity in the measured deformation-torque curve was identified as the yield stress. It should be noted that this direct measurement of the yield stress can be quite different from the value that is often reported as the yield stress, which is obtained by extrapolation of the shear stress-shear rate curve to zero shear rate. All of the measurements in this work were made at 25°C; previous work [30], which examined a range of temperatures, showed a relatively weak effect of temperature.

Measured values for viscosity at selected shear rates and the yield stress are shown in Table 2.5, viscosity versus shear rate as function of feed water content is depicted in Figure 2.1. The data show the progressive increase in feed viscosity and yield stress as the water content of the feed decreases. The rheological properties measured for the feed at 34 wt% water were deliberately near the upper limits (yield stress of 276 Pa) of the installed feed system in order to test the widest range of solids contents. In keeping with previous tests, the feed at the water content of 56 wt% was metered into the melter using a peristaltic pump without incident for the

test with plenum heaters. Feeding the slurry with a water content of 34 wt% required the use of the AOD feed system, which permitted the use of increased line pressure and higher flow rates during the feed pulses (see Section 1.3.1).

SECTION 3.0
DM100 MELTER OPERATIONS

Two melter tests were conducted on the DM100-BL between 8/30/10 and 9/10/10, one using plenum heaters the other using feed dried to 34 weight percent water. These tests produced over 800 kg of glass from over 2200 kg of feed. Prior to testing, the glass inventory was reduced from about 170 kg to about 100 kg in order to decrease the feeding time required to change over the composition of the melt pool. A glass temperature of 1200°C was used for both tests in order to compare the effects of the test variables on production rate and processing properties as well as to facilitate comparison with previously conducted tests. Both tests were also conducted with the same waste stimulant using aluminum hydroxide as the aluminum source and targeted the HLW-Al-19 glass composition. The two tests were divided as follows:

- Plenum heaters, 500 g glass per liter feed, 52 hours.
- No plenum heaters, feed dried to 34 weight percent water, 900 g glass per liter feed, 37 hours.

Summaries of the tests are provided in Table 3.1 together with results from comparable tests with the same feed composition. Attempts were made to replicate the melter configuration and operating conditions used for previous tests with HLW simulants [1-3, 10-12, 14-16, 32]. These conditions include a near-complete cold cap, which is between 80-95% melt surface coverage for the DM100 since a 100% cold cap tends to lead to "bridging" in smaller melters. The bubbling rate was fixed at 9 lpm and the feed rate was adjusted to maintain a complete cold cap. This use of bubbling is in contrast to some previous tests where the production rate was fixed between 1000 and 1050 $kg/m^2/day$ and the bubbling rate was adjusted to maintain a complete cold cap [10-12, 32]. The recently installed bubbler system at DWPF uses argon as the bubbler gas whereas the WTP baseline is bubbling with air. For the current tests, air was maintained as the bubbler gas because of the extensive amount of WTP melter test data with air bubbling, the lack of data with argon bubbling, and the potentially adverse redox effect of bubbling with argon. The approach used in the present tests in which the air bubbling rate, glass temperature, and target glass composition are held constant, provides a more direct evaluation of the effects of the use of plenum heaters and dried feed on production rate. After a short ramp up, power to the plenum heaters was about 8 kW through the majority of the first test.

Overall, there were no significant difficulties in processing these feed and glass compositions during these tests. The ADS feed system and the peristaltic pump, each of which were tapped into the recirculation line, were adequate for the high solids and nominal feeds, respectively. The cold cap conditions during the test with plenum heaters were similar to the range of conditions observed in previous tests with HLW feeds [10-12, 14-16, 32], particularly those feeds high in aluminum [1-3]. Some feeds tend to stick to the walls and can eventually form a bridge above the melt pool that is connected to opposite walls of the melter (referred to as “bridging”). Also, “shelves” (partial bridging) can form that can become disconnected from the underlying glass pool when glass is discharged, which then tend to persist and accumulate more

feed. These phenomena are typically more prevalent in smaller melters than in large production melters. The current feeds had a tendency to adhere to the melter walls to form "shelves" and "bridges," some of which required manual dislodging from the walls. Glass formulation HLWI-Al-19 [2] formed soft deposits on the walls and a fluid cold-cap, as opposed to an earlier glass formulation (HLW-E-Al-27) [1] developed for the same HLW stream that formed hard deposits and a hard, crusty cold-cap. The feed with the fluid cold-cap, HLWI-Al-19, showed better processing characteristics (less "bridging" and formation of "shelves") and higher melt rate than HLW-E-Al-27. Like the HLWI-Al-19 feed in the baseline tests [2], a more fluid cold cap and softer deposits on the walls were formed during the current tests. The high solids content feed formed a more irregular cold cap on the melt pool surface. Interruptions during the test utilizing plenum heaters totaled no more than about an hour. These short interruptions were required in order to transfer feed to the feed tank and adjust the feed line in the peristaltic pump as a result of wear from the pump rollers. Longer interruptions were encountered during the test with high solids content feed due to longer feed transfer times and time required to replace failed solenoid valves. Spikes in feed rate often occurred immediately after feed transfers due to adjustments in tank mixer speeds and pump settings. Production rates typically varied by about ten and twenty percent from the mean rate for tests using plenum heaters and high solids content feed, respectively, during steady-state feeding periods. No foamy glass was observed in the glass discharge and no foam was observed on the melt pool surface or cold cap.

Figures 3.1.a and 3.1.b illustrate the glass production rates as moving hourly and cumulative averages during testing. Steady-state production rates for current and previous tests [1, 2] conducted at the same constant bubbling rate with the same feed composition and various glass formulations are tabulated in Table 3.2; Figure 3.2 summarizes the results for tests conducted with original and selected enhanced formulations in comparison to the results from the present work. Taken together, the past and present test results show progressive increases in production rate with improvements in glass formulation, increased melt pool temperature, use of plenum heaters, and reduced feed water content. Importantly, the test results also show that significant rate enhancements were achieved as a result of using lid heaters and processing feed with reduced water contents:

- Glass production rates increased by 53% (2300 vs. 1500 kg/m^2/day) as a result of using plenum heaters

- Glass production rates increased by 100% (3000 vs. 1500 kg/m^2/day) as result of processing feed dried from 57 to 34 weight percent water.

Although some increase in glass production rate was expected as a result of using plenum heaters, the enhancement achieved in the current test was greater than previously obtained using plenum heaters on the DM100. Tests with a high aluminum SRS waste processed at 1175^{o}C glass temperature with bubbling showed only a twelve percent increase with plenum heaters [33] and tests with a high iron Hanford waste processed at 1150^{o}C glass temperature and no bubbling showed only a twenty five percent increase with plenum heaters [34]. These three data points on the effect of plenum heaters on glass production rate are from tests that also differ in many other parameters (feed composition, glass composition, feed water content, use of glass formers vs. frit, melter size, use of bubbling vs. no bubbling, plenum temperature, glass temperature, etc.). It

is therefore likely that the observed difference in improvements in processing rate with plenum heaters is due to the dependence of that effect on these other variables. Further work would be useful in separating the effects of these variables; however, without additional test data, it is not possible to unambiguously ascribe this difference to any specific variable.

Increases in production rate have also been observed in previous tests with decreasing feed water content [17]. Up to 100% increase in production rate was observed in these tests as water contents decreased from 80 to 61% and 72 to 55%. Taken together the results show a doubling of production rate in response to an absolute decrease in feed water content of 20 to 25 weight percent.

The results of various operational measurements that were made during these tests are given in Table 3.3. Glass temperatures are shown in Figures 3.3.a and 3.3.b, plenum temperatures in Figures 3.4.a and 3.4.b, electrode temperatures in Figures 3.5.a and 3.5.b, glass resistance in Figures 3.6.a and 3.6.b, melt pool bubbling in Figures 3.7.a and 3.7.b; electrode power is included in the figures with electrode temperatures and glass resistance. Bulk glass temperatures (measured at 5 and 10 inches from the bottom of the melt pool) were largely within 10°C of the target glass temperatures of 1200°C throughout the vast majority of the tests. Glass temperatures closer to the top of the melt pool (measured at 16 and 27 inches from the bottom) are not reliable indicators of bulk glass temperatures as a result of their sensitivity to variations in the level of glass in the melter and gradients near the melt surface. As a result of the intentionally lower glass level, glass temperatures measured at these locations were even lower at the beginning of the initial test, prior to the glass level in the melter being increased to above the upper pair of electrodes. Plenum temperatures averaged about 700°C and ranged from 650 to 750°C while using plenum heaters, which is about 100 to 150°C higher than for comparable tests without plenum heaters. During the test processing feed with the lower water content, plenum temperatures ranged from 500 to 650°C. Higher plenum temperatures were measured at the beginning of both tests during the development of the cold cap and during interruptions while processing the low water content feed. Plenum temperatures measured in the two thermocouples were very similar during the first test due to relatively uniform cold cap and constant source of heat supplied by the plenum heaters. Conversely, the test conducted with high solids content feed had a more irregular cold cap resulting in a 50 to 75°C difference in the plenum temperature measured at the two locations. Comparing plenum temperature of tests with “dried feed” and Tests 7 and 8 (higher water content feeds compared to the dried feed), Tests 7 and 8 show lower plenum temperatures. The test with “dried feed” has lower plenum temperature when compared to the “plenum heater” test because of the presence of plenum heaters for the “plenum heater” test. From previous experience, lower or higher water content feed is not necessarily expected to give a lower plenum temperature; it is more likely to be affected by the extent of cold-cap coverage and presence (or absence) of plenum heaters. The target bubbling rate of 9 lpm was maintained throughout the tests while slurry was actively introduced into the melter; the bubbling rate was lowered during feeding interruptions. It is worth noting that the maxima and minima in bubbling rate during a test can be misleading because the large difference can be due to a single data point. Plots of bubbling as a function of time given in Figures 3.7a and 3.7b provide better indications of any changes in bubbling rates during the tests.

The lower pair of electrodes was hotter than the upper pair of electrodes at the beginning of the first test due to the lower starting glass level. Once the melter was filled with glass above the top electrodes, the two electrode pairs were 50 to 100ºC colder than the glass pool, depending on the temperature measurement points in the glass pool and electrodes. The bottom electrode, which was not powered, was 300 to 350ºC colder than the powered side electrodes. Power supplied to the electrodes during steady-state processing was about 34 kW during both tests and averaged 33.7 and 32.1 kW for tests conducted with plenum heaters and high solids content feed, respectively. More power was required during these tests than previous tests with feed targeting the same glass composition [2, 3] as a result of the higher melt pool temperature and considerably higher glass production rates. The opposite trend is observed when power usage is normalized to glass production due to the amount of energy required to maintain the glass pool at the target melt temperature (i.e., the essentially constant idling power). This does not include the 8 kW applied to the plenum heaters during the first test. The calculated glass pool resistance decreased dramatically as the melter was filled with glass, as would be expected. During the majority of the tests, the melt pool resistance was relatively constant between 0.065 and 0.085 ohms as a result of the lack of compositional change and constant glass pool temperature of 1200°C.

The gas temperature at the film cooler averaged between 275-287ºC and depended on the plenum temperature, the amount of added film cooler air, and the temperature of the added film cooler air. Drops of less than seventeen degrees in gas temperature were observed across the (insulated) transition line; the high temperature is maintained in order to prevent condensation in the downstream filtration units.

SECTION 4.0
FEED SAMPLE AND GLASS PRODUCT ANALYSIS

4.1 Analysis of Feed Samples

4.1.1 General Properties

Feed samples from each test were analyzed to confirm physical properties and chemical composition. Samples were taken during melter testing from either an inline sampling port or directly from the feed drum. Sample names and measured properties are given in Table 4.1. Density, pH, water content, glass conversion ratio, and oxide composition by XRF and DCP were measured on all samples. The measured glass conversion ratios for all feed samples were within six percent of the target on a weight per weight basis, validating the use of the target conversion ratio for calculating glass production rates. The water content, density, glass yield, and pH varied within a narrow range for feed from each of the two tests. Measured values for the first test are also very similar to the analysis of samples from previous tests with the same feed. As expected, glass yield and density are significantly higher for feed with low water content.

4.1.2 Chemical Composition

The methods used for analysis of feed sample chemical compositions are described in Section 1.4. The boron, fluorine, and lithium oxide target values were used for normalizing the XRF data since their concentrations were not determined by XRF. These results, compared to the target composition in Table 4.2, generally corroborate the consistency of the feed compositions and show good agreement with the target compositions for the major elements. All oxides with target concentrations greater than one percent deviated by less than 10% from target. The composition of this feed is further corroborated by comparison to the product glasses (see Section 4.2.1), which shows all oxides with concentrations greater than 1 wt% in the target composition to be within about 10% of the target.

Low concentrations of manganese and strontium were measured even though they are not included in the target composition. Also, common elements such as magnesium, titanium, zirconium, potassium, and chromium, when targeted at low concentrations, were typically above these targets. These positive deviations are often observed in melter feeds due to their ubiquity in the raw materials used to make up the simulants and in the glass forming additives. No cadmium was measured in the feed samples as a result of the concentrations being below the sensitivity of the XRF for these glass matrices [2]. However, as discussed below, DCP analysis indicates that cadmium is present at the low target concentrations. Analyzed sulfur concentrations are below target concentrations due to volatilization during sample preparation.

Corroborative analysis using DCP on solutions of acid-dissolved glass was performed on select glasses produced from each test; the results are compared to the XRF analysis in Table 4.3.

Values for most oxides compare favorably with the XRF analysis and target composition except for sodium, which often exhibits a low bias using this procedure [31]; consequently, the XRF values are to be preferred. Low biases for aluminum and chromium using the DCP method were also observed in previous tests with high aluminum feeds [2, 3]. Cadmium was detected in samples at near target concentrations. The closeness of the DCP boron and lithium analyses to the target (deviations less than 7%) validates the use of the target boron and lithium concentrations for normalizing the XRF data.

4.2 Analysis of Glass Samples

Over 800 kg of glass was produced through the DM100 in these tests. The glass was discharged from the DM100 periodically into 5-gallon carbon steel pails using an airlift system. The discharged product was sampled by removing sufficient glass from the top of each pail for total inorganic analysis. Product glass masses, discharge date, and analysis performed are given in Table 4.4.

4.2.1 Compositional Analysis of Discharge Glasses

All discharge glass samples were crushed and analyzed directly by XRF. The target values for boron and lithium oxides, which are not determined by XRF, were used for normalizing the XRF data to 100 wt%. Fluorine content is also not determined by the standard XRF procedure but requires a polished monolith sample as opposed to the standardized ground glass preparation used for the other elements. In the current tests, that analysis was not performed and instead the steady-state fluorine concentration measured in previous tests processing the same glass composition was assumed [2]. The XRF analyzed compositions of discharged glass samples are provided in Table 4.5. The majority of the XRF analysis results compare very favorably to their corresponding target values and feed sample analyses (see Section 4.1.2). Oxides with a target concentration greater than one weight percent showed below 10% deviation from the target values once the glass pool composition transitioned to that of the feed composition. Similar to the feed sample analyses, common elements such as magnesium, titanium, zirconium, and potassium targeted at low concentrations were above their respective targets. Manganese was present in the melt pool prior to these tests but was not included in the current target composition. Sulfur concentrations are below target for all glasses due to volatilization from the glass pool and cold cap.

Compositional trends for selected constituents shown in Figures 4.1.a - 4.1.c illustrate the closeness to targets at the end of tests with each composition. Exceptions include volatile species such as sulfur, which remain significantly below their target concentrations as a result of significant release to the melter exhaust. At the onset of testing, aluminum, boron, bismuth, and calcium increase in concentration at the expense of silicon, iron, sodium, lithium, and titanium as the steady-state composition is approached. Although not depicted in the figures, manganese, which is present in the melt pool at the beginning of testing but is not present in the target glass composition, decreases in concentration to the level of trace contamination measured in feed

samples. The concentrations of most oxides do not undergo large changes during testing since the glass composition is constant and significant additive changes occur mostly for only boron and silicon.

SECTION 5.0
MONITORED OFF-GAS EMISSIONS

5.1 Particulate Sampling

The melter exhaust was sampled for metals/particles according to 40-CFR-60 Methods 3, 5, and 29 at steady-state operating conditions during each test segment. The concentrations of off-gas species that are present as particulates and gaseous species that are collected in impinger solutions were derived from laboratory data on solutions extracted from air samples (filters and various solutions) together with measurements of the volume of air sampled. Particulate collection required isokinetic sampling, which entails removing gas from the exhaust at the same velocity that the air is flowing in the duct (40-CFR-60, Methods 1-5). Typically, a sample size of 30 dscf was taken at a rate of between 0.5 and 0.75 dscfm. Total particulate loading was determined by combining gravimetric analysis of the standard particle filter and chemical analysis of probe rinse solutions. An additional impinger containing 2 N NaOH was added to the sampling train to ensure complete scrubbing of all acid gases and, particularly, iodine. The collected materials were analyzed using direct current plasma atomic emission spectroscopy for the majority of the constituents and ion chromatography (IC) for anions. Melter emission fluxes are compared to feed fluxes and previous emission samples taken while processing the same glass composition in Table 5.1. Notice the distinction that is made between constituents sampled as particles and as "gas". The "gaseous" constituents are operationally defined as those species that are scrubbed in the impinger solutions after the air stream has passed through a 0.3 μm heated filter. Both samples are well within the 90 – 110% limits for isokinetic sampling.

Particulate emissions constituted 0.14 to 0.23 percent of feed solids. This level of carryover is less than that measured for previous tests with chromium, bismuth, aluminum, and aluminum plus sodium limited HLW wastes (0.06 – 0.57) [1], HLW AZ-102 (0.57 - 1.47 percent) [13], and HLW C-106/AY-102 SIPP (0.61 to 0.81 percent) [12] simulants processed on the same melter. The higher carryover in many of the previous tests is due to higher proportions of volatile species in the feed such as rhenium, cesium, and halogens. The carryover is lower but still comparable to previous tests conducted with HLW AZ-101 simulants while bubbling the melt pool [34]. In tests with the same waste and similar glass compositions, solids carryover values were within the same ranges, 0.04 – 0.29 [2] and 0.09 – 0.48 [3], with the higher concentrations at higher added reductant concentrations. Specific comparisons provided in Table 5.1 and Figure 5.1 show the effect of plenum heaters and processing low water content feed for the same glass composition (enhanced formulation, HWI-Al-19). Testing with this glass composition shows about a two fold increase (0.05 to 0.12) in percent carryover with a 50°C increase in glass temperature, a near two fold increase (0.12 to 0.23) in percent carryover with the use plenum heaters, and little increase while processing dried feed (0.12 to 0.14). In previous tests with various HLW waste streams, carryover decreased with decreasing feed water content [2, 17, 34] due presumably to increased entrainment with higher water content. This was not observed in the low water content feed in these tests due in part to the uneven nature of the cold cap.

As expected, the feed elements emitted at the lowest melter DF were clearly fluorine and sulfur. Another element exhibiting some volatile behavior was boron. The relative volatility of barium, cadmium, potassium, magnesium, and titanium are difficult to evaluate due to the low target concentrations and trace contamination in the feed. Boron, sulfur, and fluorine were the only elements detected in the impinger solutions collected downstream of the heated particle filter in the sampling train, which constitutes the "gas" fraction of the melter emissions.

5.2 Gases Monitored by FTIR

Melter emissions were monitored in each test for a variety of gaseous components, most notably CO and nitrogen species, by Fourier Transform Infra-Red Spectroscopy (FTIR). The off-gas system temperature is maintained well above 100°C beyond the sampling port downstream of the DM100 HEPA filter to prevent analyte loss due to condensation prior to monitoring. The data, therefore, represent the relative concentrations of volatile gaseous species in the melter exhaust. A summary of the range and average concentrations of gaseous species monitored during the DM100 tests is provided in Table 5.2; results from previous tests with the same feed composition are also provided. The analytes listed in Table 5.2 are those that were thought likely to be observed during the tests based on previous work; no other species were detected in the off-gas stream by FTIR. The concentrations of three monitored species, nitrogen monoxide, hydrogen fluoride, and water are plotted in Figures 5.2 - 5.4. Generally, emissions from the DM100 were relatively low as a result of the low concentrations of nitrogen, organic carbon, ammonia, and halogens in the feed. The most abundant nitrogen species monitored was NO, which is in keeping with previous melter tests with both HLW and LAW feeds. Little or no nitrogen was detected as other species, except for NO_2, which was 6 to 12 times lower in concentration than NO. The lower ratio was measured during the test with dried feed and the same ratio was measured in DM1200 tests [2]. The variability in the NO concentrations shown in Figure 5.2 is attributable to the dynamic conditions in the cold cap and is in keeping with previous melter tests. The concentration of water in the melter exhaust increased with increasing feed rate except in the test processing feed with low moisture content. Consistent with the gaseous fluorine concentrations observed using the Method 5-type sampling (see Section 5.1), HF was observed throughout the testing by FTIR. The variations in emissions over the course of each test segment are due in part to changes in the melt pool cold cap. Hydrogen fluoride concentrations were lower at the beginning of testing due to the lack of fluorine in the glass pool and the processing time required for the glass to reach steady-state concentration with respect to fluorine. Also consistent with the Method 5-type results, low sulfur dioxide concentrations were monitored in each test; however, gaseous sulfur emissions can also be present in forms other than sulfur dioxide that are not monitored by the FTIR, such as sulfuric acid.

SECTION 6.0
SUMMARY AND CONCLUSIONS

DM100 melter tests were conducted to determine the effect of plenum heaters and very high solids content on feed processing characteristics and glass production rate for a high-aluminum Hanford HLW glass formulation [2, 3]. The glass formulation used in this work was previously developed and tested for ORP under nominal WTP melter operating conditions and meets all of the processing and product quality requirements for WTP HLW glass. The same melter was used in the present tests thus providing comparisons between the previously collected data on melter processing characteristics and partitioning to the off-gas.

Two DM100 melter tests were performed that produced over 800 kg of glass from over 2000 kg of feed. Both tests were conducted at a nominal melter operating temperature of 1200ºC with the same HLW high aluminum formulation [2, 3] and fixed 9 lpm bubbling to evaluate the effects of plenum heaters and high feed solids content on glass production rate. Overall, there were no significant difficulties in processing these feed and glass compositions during these tests. The ADS feed system and the peristaltic pump, which were tapped into the recirculation line, were adequate for the high solids and nominal feeds, respectively. The cold cap conditions during the test with plenum heaters were similar to the range of conditions observed in previous tests with HLW feeds [10-12, 14-16, 32], particularly those feeds high in aluminum [2, 3]. The feeds had a tendency to adhere to melter walls to form "shelves" and "bridges," some of which required manual dislodging from the walls. Analysis of glass samples discharged from the melter confirmed the closeness of the glass composition to the target. Key results from the tests include the following:

- Glass production rate with plenum heaters increased by 53% to 2300 kg/m^2/day from 1500 kg/m^2/day for the previous test without plenum heaters [2, 3].

- Glass production rate increased by 100% to 3000 kg/m^2/day from 1500 kg/m^2/day [2, 3] as the water content in the feed was reduced from 57 to 34 weight percent.

- Solids carryover showed a near two fold increase (0.12% to 0.23%) with the use plenum heaters and little increase while processing dried feed (0.12% to 0.14%).

Although an increase in glass production rate was expected as a result of using plenum heaters, the enhancement achieved in the current test was greater than previously obtained using plenum heaters on the DM100. Tests with a high aluminum SRS waste processed at 1175ºC glass temperature with bubbling showed only a twelve percent increase with plenum heaters [33] and tests with a high iron Hanford waste processed at 1150 ºC glass temperature and no bubbling showed only a twenty five percent increase with plenum heaters [34]. Increases in production rate have also been observed in previous tests with decreasing feed water content [17]. Up to 100% increase in production rate was observed in these tests as water contents decreased from 80 to 61% and 72 to 55%. Taken together the results show a doubling of production rate in

response to an absolute decrease in feed water content of 20 to 25 percent.

In previous tests with various HLW waste streams, carryover decreased with decreasing feed water content [2, 17, 34] due presumably to increased entrainment with higher water content. This was not observed for the low water content feed in these tests due in part to the uneven nature of the cold cap.

The glass production rates observed in the current tests of 2300 kg/m^2/day with plenum heaters and feed with nominal solids content, and 3000 kg/m^2/day with the high solids content feed are both well above the WTP baseline goal of 800 kg/m^2/day and the stretch goal of 1000 kg/m^2/day. The higher production rates demonstrated in these tests have the potential to substantially increase HLW processing rate at the WTP. These data, in combination with data on other potential enhancements, such as the use of increased operating temperature by using improved high temperature melter materials of construction, provide valuable information for use in decisions regarding the selection of specific enhancements to optimize the performance of a next generation HLW melter for the WTP in order to achieve improved waste treatment capability.

The current, and previous, glass development work and melter tests for WTP have identified various methods to improve the processing rate of HLW at Hanford. The specific methods that are most advantageous will depend on the level of improvement that is desired and the associated extent of facility modification that may be required to support increased melter processing rates. Starting from the WTP baseline rate of 800 kg/m^2/day of glass production at a nominal operating temperature of 1150°C, we would recommend the following approaches to achieve various levels of melter processing rate improvements for HLW feeds:

- 0 to 25% Improvement
  - Glass formulation optimization for better processing rate
  - Optimization of bubbling in the WTP HLW melters

- 25 to 50% Improvement
  - Glass formulation optimization for better processing rate
  - Optimization of bubbling in the WTP HLW melters
  - Slightly higher operating temperature (25 °C increase to 1175°C)

- 50 to 100% Improvement
  - Glass formulation optimization for better processing rate
  - Optimization of bubbling in the WTP HLW melters
  - Moderately higher operating temperature (25 to 50°C increase to 1175 to 1200°C).

The higher end of this range of melter processing rate improvements would likely challenge the installed capacity of some of the WTP supporting systems and could require significant facility modifications to realize.

SECTION 7.0
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Table 2.1. Oxide Compositions of Limiting Waste Streams (wt%).

Waste Component	Bi Limited	Cr Limited	Al Limited	Al and Na Limited
Al_2O_3	22.45%	25.53%	49.21%	43.30%
B_2O_3	0.58%	0.53%	0.39%	0.74%
CaO	1.61%	2.47%	2.21%	1.47%
Fe_2O_3	13.40%	13.13%	12.11%	5.71%
Li_2O	0.31%	0.36%	0.35%	0.15%
MgO	0.82%	0.16%	0.24%	0.44%
Na_2O	12.97%	20.09%	7.35%	25.79%
SiO_2	12.04%	10.56%	10.05%	6.22%
TiO_2	0.30%	0.01%	0.02%	0.35%
ZnO	0.31%	0.25%	0.17%	0.36%
ZrO_2	0.40%	0.11%	0.81%	0.25%
SO_3	0.91%	1.52%	0.41%	0.44%
Bi_2O_3	12.91%	7.29%	2.35%	2.35%
ThO_2	0.25%	0.04%	0.37%	0.04%
Cr_2O_3	1.00%	3.07%	1.07%	1.44%
K_2O	0.89%	0.37%	0.29%	1.34%
U_3O_8	3.48%	7.59%	7.25%	4.58%
BaO	0.02%	0.03%	0.11%	0.06%
CdO	0.00%	0.01%	0.05%	0.02%
NiO	3.71%	1.06%	0.82%	0.20%
PbO	0.48%	0.48%	0.84%	0.18%
P_2O_5	9.60%	3.34%	2.16%	4.10%
F-	1.58%	2.00%	1.37%	0.46%
Total	100.00%	100.00%	100.00%	100.00%

Table 2.2. Compositions of the Al-Limited Waste (Oxide Basis) and the HLW Waste Simulant to Produce 100 kg of Waste Oxides (20 wt% suspended solids) Using $Al(OH)_3$ as the Aluminum Source.

Al-Limited Waste Composition		Al-Limited HLW Waste Simulant	
Waste Oxide	**Wt%**	**Starting Materials**	**Target Weight (kg)** [*]
Al_2O_3	49.21%	$Al(OH)_3$	76.052
B_2O_3	0.39%	H_3BO_3	0.700
CaO	2.21%	CaO	2.255
Fe_2O_3	12.11%	$Fe(OH)_3$ (13% Slurry)	99.643
Li_2O	0.35%	Li_2CO_3	0.888
MgO	0.24%	MgO	0.253
Na_2O	7.35%	NaOH	4.235
SiO_2	10.05%	SiO_2	10.152
TiO_2	0.02%	TiO_2	0.020
ZnO	0.17%	ZnO	0.172
ZrO_2	0.81%	$Zr(OH)_4{\cdot}xH_2O$	2.093
SO_3	0.41%	Na_2SO_4	0.735
Bi_2O_3	2.35%	Bi_2O_3	2.374
ThO_2	0.37%	Th Surrogate	0
Cr_2O_3	1.07%	$Cr_2O_3{\cdot}1.5H_2O$	1.273
K_2O	0.29%	KNO_3	0.632
U_3O_8	7.25%	U Surrogate	0
BaO	0.11%	$BaCO_3$	0.143
CdO	0.05%	CdO	0.051
NiO	0.82%	$Ni(OH)_2$	1.055
PbO	0.84%	PbO	0.848
P_2O_5	2.16%	$FePO_4{\cdot}xH_2O$	5.738
F	1.37%	NaF	3.044
Carbonate	1.20[#]	Na_2CO_3	0.806
Nitrite	0.50	$NaNO_2$	0.769
Nitrate	2.00	$NaNO_3$	2.230
Organic Carbon	0.05	$H_2C_2O_4{\cdot}2H_2O$	0.264
—	—	Water	279.400[4]
—	—	—	—
TOTAL	100.0%	TOTAL	495.825[4]

[*] Target weights adjusted for assay information of starting materials
[#] Unit for volatile components is g/100 g of waste oxide
— Empty data field

Table 2.3. Composition and Properties of Aluminum Limited Waste and Glass Formulation HWI-Al-19 with 45% Waste Loading (wt%).

-	Al-Limited Waste*	Waste in Glass	Glass Forming Additives	Target Glass HWI-Al-19
Al_2O_3	53.27	23.97	-	23.97
B_2O_3	0.42	0.19	19.00	19.19
BaO	0.12	0.05	-	0.05
Bi_2O_3	2.54	1.14	-	1.14
CaO	2.39	1.08	4.50	5.58
CdO	0.05	0.02	-	0.02
Cr_2O_3	1.16	0.52		0.52
F	1.48	0.67	-	0.67
Fe_2O_3	13.11	5.90	-	5.90
K_2O	0.31	0.14	-	0.14
Li_2O	0.38	0.17	3.40	3.57
MgO	0.26	0.12	-	0.12
Na_2O	7.96	3.58	6.00	9.58
NiO	0.89	0.40	-	0.40
P_2O_5	2.34	1.05	-	1.05
PbO	0.91	0.41	-	0.41
SO_3	0.44	0.20	-	0.20
SiO_2	10.88	4.90	22.10	27.00
TiO_2	0.02	0.01	-	0.01
ZnO	0.18	0.08	-	0.08
ZrO_2	0.88	0.39	-	0.39
Sum	100.0	45.00	55.00	100.0#

* Renormalized from Ref. [5] after removal of radioactive components.
# The sum does not equal to 100.00 because of rounding of decimals.

Viscosity @1150ºC, P			33
Conductivity @1150ºC, S/cm			0.27
Crystal Content, As Melted			None
Crystal Content, 72 hr at 950°C			1.3
Crystal Content, CCC			1.9
TCLP			Pass
PCT, g/L	-	DWPF-EA	HWI-Al-19
	B	16.7	0.654
	Li	9.6	0.794
	Na	13.3	0.624

- Empty data field

Table 2.4. Composition of Melter Feed to Produce 100 kg of Target Glass HWI-Al-19 (Target Glass Yield = 500 g/L Feed) from the Al-Limited Waste Simulant Using $Al(OH)_3$ as the Aluminum Source.

Al-Limited Waste Simulant		Glass-Forming Additives	
Starting Materials	**Target Weight (kg)***	**Starting Materials**	**Target Weight (kg)***
$Al(OH)_3$	37.047	—	—
H_3BO_3	0.341	H_3BO_3	34.089
$BaCO_3$	0.070	—	—
Bi_2O_3	1.156	—	—
CaO	1.099	$CaSiO_3$ (Wollastonite)	9.798
CdO	0.025	—	—
Cr_2O_3	0.532	—	—
NaF	1.483	—	—
$Fe(OH)_3$ (13% Slurry)	48.539	—	—
KNO_3	0.308	—	—
Li_2CO_3	0.432	Li_2CO_3	8.625
MgO	0.121	—	—
NaOH	2.190	Na_2CO_3	10.364
$Ni(OH)_2$	0.514	—	—
$FePO_4{\cdot}xH_2O$	2.795	—	—
PbO	0.413	—	—
Na_2SO_4	0.358	—	—
SiO_2	4.945	SiO_2	17.276
TiO_2	0.010	—	—
ZnO	0.084	—	—
$Zr(OH)_4{\cdot}xH_2O$	1.020	—	—
H_2O	91.903	—	—
Na_2CO_3	0.314	—	—
$NaNO_2$	0.346	—	—
$NaNO_3$	0.984	—	—
$H_2C_2O_4{\cdot}2H_2O$	0.119	—	—
—[2]	—	—	—
Simulant Total	197.148	Additives Total	80.152
—	—	FEED TOTAL	277.300

* Target weights adjusted for assay information of starting materials
— Empty data field

Table 2.5. Rheological Properties of Melter Feed Samples Over a Range of Feed Water Contents.

Date	Name	% Water	Yield Stress (Pa)	Viscosity (Poise)		
				@1/s	@10/s	@100/s
8/25/10	GBL-F-127E	34	275.8	178.0	161.1	28.10
8/31/10	GBL-F-148A-2	40	91.5	109.3	14.86	3.28
8/25/10	GBL-F-127D	47	5.1	20.81	2.65	0.57
8/25/10	GBL-F-127F	49	7.7	17.88	2.46	0.57
6/24/10	BLY-F-141A	56	1.1	2.72	0.39	0.14

Table 3.1. Summary of Results from DM100 Tests with HWI-Al-19 (45 wt% Waste Loading) and Aluminum Hydroxide.

Test		Plenum Heaters	Dried Feed	Baseline [2]	Baseline [2]
Time	Feed Start	8/30/10 12:45	9/8/10 18:10	6/23/08 7:56	6/25/08 12:15
	Feed End	9/1/10 17:00	9/10/10 7:07	6/25/08 11:30	6/27/08 23:30
	Interval	52.3 hr	37.0 hr	51.6 hr	59.25 hr
Water Feeding for Cold Cap		30 min	20 min	64 min	NA
Slurry Feeding		51.8 hr	36.7 hr	50.5 hr	59.25 hr
Feeding Interruptions		26 min	292 min	38 min	13 min
Target Glass Temperature		1200 °C	1200 °C	1200 °C	1150 °C
Average Bubbling Rate		9.1 lpm	7.9 lpm	9.0 lpm	9.0 lpm
Feed	Used	1409 kg	860 kg	902 kg	693 kg
	Target Glass yield	500 g/l	900 g/l	500 g/l	500 g/l
		0.361 kg/kg	0.535 kg/kg	0.361 kg/kg	0.361 kg/kg
	Average Feed Rate	27.2 kg/hr	23.4 kg/hr	17.9 kg/hr	11.7 kg/hr
Glass Produced	Poured	399 kg	416 kg	245 kg	239 kg
	Average Rate*	2185 kg/m^2/day	2736 kg/m^2/day	1434 kg/m^2/day	938 kg/m^2/day
	Steady State Rate*	2300 kg/m^2/day	3000 kg/m^2/day	1500 kg/m^2/day	950 kg/m^2/day
	Average Power Use	3.4 kW hr/kg glass	2.6 kW hr/kg glass	4.1 kW hr/kg glass	4.6 kW hr/kg glass

*- Rates calculated from feed data.
Note: Rates do not take into account the time for water feeding and cold cap burn-off.

Table 3.2. Steady-State Production Rates Achieved with High Aluminum Waste Composition on the DM100 at Melt Pool Bubbling of 9 lpm.

HLW Waste	Feed Solids Content (g glass/liter)	Glass Temperature (^{o}C)	Production Rate kg/m^2/day
Aluminum Limited (HLW-E-Al-27 Glass Composition) [1]	500	1200	1200
		1150	700
Aluminum Limited (HWI-Al-16, Glass Composition) [2]	500	1200	1400
		1150	950
Aluminum Limited (HWI-Al-19, Glass Composition) [2]	500	1200	1500
		1150	950
Aluminum Limited (HWI-Al-19, Glass Composition) This work	500	1200, plenum heat	2300
	850 (dried feed)	1200	3000

Table 3.3. Summary of Measured DM100 Parameters.

Test			Plenum Heaters			Dried Feed		
			AVG	MIN	MAX	AVG	MIN	MAX
TEMPERATURE (°C)	Electrode	East Upper	1065	690	1126	1111	1086	1133
		West Upper	1053	711	1115	1097	1076	1116
		West Lower	1142	1127	1174	1127	1104	1144
		Bottom	800	765	813	769	720	794
	Glass	27” from bottom	1107	433	1206	1180	1090	1236
		16” from bottom	1144	417	1214	1192	1142	1241
		10” from bottom	1193	1135	1225	1198	1155	1247
		5” from bottom	1203	1177	1223	1204	1171	1248
	Plenum	Exposed	715	646	829	633	409	908
		Thermowell	697	629	802	576	469	798
	Discharge	Chamber	1028	982	1066	1004	969	1042
		Air Lift	1043	941	1146	1053	974	1153
	Film Cooler Outlet		276	257	301	291	216	335
	Transition Line Outlet		262	251	289	283	240	318
Lance Bubbling (lpm)			9.1	1.8	9.5	7.9	1.5	9.2
Melter Pressure (inches water)			-0.84	-2.02	0.24	-2.17	-4.78	5.08
Total Electrode Voltage (V)			47.6	1.0	50.9	48.9	35.3	55.1
Total Electrode Power (kW)			33.7	0.0	37.7	32.1	19.0	36.3
Glass Resistance (ohms)			0.067	0.057	0.085	0.075	0.062	0.086

Table 3.3. Summary of Measured DM100 Parameters (continued).

Test			7			8		
			AVG	MIN	MAX	AVG	MIN	MAX
TEMPERATURE (°C)	Electrode	East Upper	1042	482	1156	1087	1067	1141
		West Upper	1107	716	1170	1103	1084	1169
		West Lower	1134	1114	1150	1081	1068	1143
		Bottom	714	655	733	702	693	733
	Glass	27” from bottom	1058	323	1202	1120	1075	1176
		16” from bottom	1118	240	1204	1133	1096	1183
		10” from bottom	1190	1150	1214	1146	1122	1200
		5” from bottom	1202	1173	1219	1153	1132	1210
	Plenum	Exposed	505	417	655	446	345	626
		Thermowell	468	397	622	413	343	596
	Discharge	Chamber	1061	1004	1099	1060	978	1084
		Air Lift	1065	962	1162	1062	1007	1115
	Film Cooler Outlet		285	281	296	279	268	287
	Transition Line Outlet		273	232	283	268	213	274
Lance Bubbling (lpm)			9.0	1.5	9.1	9.0	8.9	9.5
Melter Pressure (inches water)			-0.97	-3.20	0.80	-0.99	-2.86	0.38
Total Electrode Voltage (V)			47.2	1.2	57.0	41.5	28.9	45.2
Total Power (kW)			26.3	10.6	28.2	18.8	10.0	26.0
Glass Resistance (ohms)			0.086	0.072	0.136	0.092	0.078	0.101

Table 4.1. Characteristics of Melter Feed Samples with the HWI-Al-19 Feed Composition and $Al(OH)_3$ as an Aluminum Source.

Test	Name	% Water	pH	Density (g/ml)	Glass Yield (g/l)	Glass Yield (kg/kg)		%Dev. From Target
						Target	Measured	
Plenum Heaters	GBL-F-129B	57.32	8.55	1.38	469	0.361	0.340	-5.82
	HBL-F-19A	55.84	8.91	1.39	490	0.361	0.353	-2.22
Dried Feed	GBL-F-148A	33.90	8.42	1.68	894	0.525	0.532	1.33
	HBL-F-19B	36.19	8.44	1.64	843	0.525	0.514	-2.06
Baseline Feed [2]		57.02	8.14	1.38	485	0.361	0.350	-3.08

Table 4.2. XRF Analyzed Compositions of Vitrified Melter Feed Samples (wt%).

Constituent	Target	Plenum Heaters		Dried Feed		Average	% Dev. From Target
		GBL-F-127B	HBL-F-19A	GBL-F-148A	HBL-F-19B		
Al_2O_3	23.97	22.37	22.16	22.33	22.09	22.24	7.23
B_2O_3*	19.19	19.19	19.19	19.19	19.19	19.19	NC
BaO	0.05	0.06	0.07	0.06	0.06	0.06	NC
Bi_2O_3	1.14	1.23	1.10	1.21	1.20	1.18	-3.83
CaO	5.58	5.66	5.46	5.66	5.69	5.62	-0.70
CdO	0.02	0.00	0.00	0.00	0.00	0.00	NC
Cr_2O_3	0.52	0.66	0.64	0.66	0.65	0.65	NC
F*	0.67	0.67	0.67	0.67	0.67	0.67	NC
Fe_2O_3	5.90	6.41	6.62	6.37	6.56	6.49	-9.93
K_2O	0.14	0.19	0.20	0.19	0.19	0.19	NC
Li_2O*	3.57	3.57	3.57	3.57	3.57	3.57	NC
MgO	0.12	0.32	0.39	0.36	0.34	0.35	NC
MnO	§	0.02	0.03	0.02	0.04	0.03	NC
Na_2O	9.58	10.30	9.64	9.72	9.21	9.72	-1.42
NiO	0.40	0.43	0.42	0.42	0.42	0.42	NC
P_2O_5	1.05	1.11	1.12	1.13	1.13	1.12	-6.99
PbO	0.41	0.37	0.40	0.47	0.39	0.41	0.46
SiO_2	27.00	26.61	27.52	27.14	27.81	27.27	-0.98
SO_3	0.20	0.16	0.17	0.17	0.19	0.17	NC
SrO	§	0.00	0.01	0.01	0.01	0.01	NC
TiO_2	0.01	0.05	0.04	0.04	0.05	0.05	NC
ZnO	0.08	0.09	0.09	0.09	0.09	0.09	NC
ZrO_2	0.39	0.54	0.49	0.52	0.46	0.50	NC
Sum	100.00	100.00	100.00	100.00	100.00	100.00	NC

* Target values
§ - Not a target constituent
NC – Not calculated.

Table 4.3. Comparison of XRF and DCP Analyzed Compositions of Vitrified Melter Feed Samples (wt%).

Constituent	Target	Plenum Heaters		Dried Feed	
		GBL-F-129B		HBL-F-19B	
		XRF	DCP	XRF	DCP
Al_2O_3	23.97	22.68	21.52	22.16	21.25
B_2O_3*	19.19	19.19	18.63	19.19	18.09
BaO	0.05	0.07	0.07	0.07	0.07
Bi_2O_3	1.14	1.05	1.05	1.10	1.19
CaO	5.58	5.47	4.77	5.46	4.83
CdO	0.02	<0.01	0.03	<0.01	0.03
Cr_2O_3	0.52	0.64	0.40	0.64	0.38
F*	0.67	0.67	NA	0.67	NA
Fe_2O_3	5.90	6.52	5.79	6.62	5.60
K_2O	0.14	0.20	0.21	0.20	0.21
Li_2O*	3.57	3.57	3.33	3.57	3.63
MgO	0.12	0.35	0.41	0.39	0.45
MnO	§	0.04	0.04	0.03	0.04
Na_2O	9.58	9.40	8.67	9.64	8.54
NiO	0.40	0.40	0.34	0.42	0.35
P_2O_5	1.05	1.12	1.00	1.12	1.21
PbO	0.41	0.37	0.46	0.40	0.49
SiO_2	27.00	27.46	28.76	27.52	28.44
SO_3	0.20	0.17	NA	0.17	NA
SrO	§	<0.01	<0.01	0.01	0.01
TiO_2	0.01	0.05	0.05	0.04	0.06
ZnO	0.08	0.09	0.09	0.09	0.07
ZrO_2	0.39	0.48	0.58	0.49	0.62
Sum	100.00	100.00	96.20	100.00	95.56

* Target values for XRF analyzed compositions
§ - Not a target constituent
NA – Not analyzed

Table 4.4. Listing of Glass Discharged, Masses, and Analysis Performed.

Test	Additive	Date	Name	Analysis	Mass (kg)	Cumulative Mass (kg)
Plenum Heaters		8/30/10	GBL-G-143A	-	-	-
		8/31/10	GBL-G-146A	XRF, DCP	32.50	32.50
			GBL-G-146B	-	-	-
			GBL-G-146C	XRF	30.62	63.12
			GBL-G-147A	-	-	-
			GBL-G-147B	XRF	23.12	86.24
			GBL-G-147C	-	-	-
			GBL-G-148A	XRF	27.46	113.70
			GBL-G-148B	-	-	-
			GBL-G-148C	XRF	21.30	135.00
		8/31/10	HBL-G-5A	-	-	-
			HBL-G-5B	XRF	28.24	163.24
			HBL-G-5C	-	-	-
			HBL-G-5D	XRF	28.26	191.50
			HBL-G-7A	-	-	-
			HBL-G-7B	XRF	24.96	216.46
			HBL-G-7C	-	-	-
		9/1/10	HBL-G-7D	XRF	25.70	242.16
			HBL-G-14A	-	-	-
			HBL-G-14B	XRF	25.72	267.88
			HBL-G-14C	-	-	-
			HBL-G-14D	XRF	26.50	294.38
			HBL-G-15A	-	-	-
			HBL-G-15B	XRF	23.72	318.10
			HBL-G-15C	-	-	-
			HBL-G-17A	XRF	34.76	352.86
			HBL-G-17B	-	-	-
			HBL-G-17C	XRF	28.96	381.82
			HBL-G-17D	XRF	17.52	399.34
Dried Feed		9/8/10	HBL-G-39A	-	-	-
			HBL-G-40A	XRF	31.78	431.12
			HBL-G-40B	-	-	-
			HBL-G-40C	-	-	-
			HBL-G-41A	XRF	30.90	462.02
		9/9/10	HBL-G-42A	-	-	-
			HBL-G-42B	XRF	24.28	486.30
			HBL-G-44A	-	-	-
			HBL-G-44B	XRF	26.18	512.48
			HBL-G-45A	-	-	-
			HBL-G-48A	XRF	32.92	545.40
			HBL-G-48B	-	-	-
			HBL-G-49A	XRF	26.44	571.84
			HBL-G-49B	-	-	-

- Empty data field

Table 4.4. List of Glass Discharged, Masses, and Analysis Performed (Continued).

Test	Additive	Date	Name	Analysis	Mass (kg)	Cumulative Mass (kg)
Dried Feed		9/9/10	HBL-G-49C	XRF	21.82	593.66
			HBL-G-50A	-	-	-
			HBL-G-50B	XRF	25.76	619.42
			HBL-G-50C	-	-	-
			HBL-G-50D	XRF	21.82	641.24
			HBL-G-50E	-	-	-
			HBL-G-55A	XRF	34.48	675.72
			HBL-G-56A	-	-	-
			HBL-G-56B	XRF	32.22	707.94
			HBL-G-57A	-	-	-
		9/10/10	HBL-G-57B	XRF	24.00	731.94
			HBL-G-57C	-	-	-
			HBL-G-57D	XRF	29.06	761.00
			HBL-G-59A	-	-	-
			HBL-G-59B	XRF	24.72	785.72
			HBL-G-59C	-	-	-
			HBL-G-59D	XRF	30.06	815.78

- Empty data field

Table 4.5. XRF Analyzed Compositions for Glass Discharged During DM100 Melter Test (wt%).

Test	Plenum Heaters										
Glass (kg)	Target	32.5	63.12	86.24	113.7	135.0	163.2	191.5	216.46	242.16	267.88
Constituent		GBL-G-146A	GBL-G-146C	GBL-G-147B	GBL-G-148A	GBL-G-148C	HBL-G-5B	HBL-G-5D	HBL-G-7B	HBL-G-7D	HBL-G-14B
Al_2O_3	23.97	20.50	20.74	21.16	21.49	21.64	21.41	21.79	21.88	21.96	22.09
B_2O_3*	19.19	14.17	14.96	15.47	15.99	16.35	16.76	17.12	17.38	17.63	17.83
BaO	0.05	0.07	0.08	0.09	0.07	0.07	0.08	0.07	0.07	0.07	0.06
Bi_2O_3	1.14	0.67	0.81	0.85	0.88	0.93	0.99	1.00	1.06	1.09	1.09
CaO	5.58	3.84	4.33	4.55	4.64	4.71	4.99	4.99	5.18	5.28	5.36
CdO	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cr_2O_3	0.52	0.50	0.54	0.52	0.53	0.54	0.56	0.55	0.57	0.57	0.58
F	0.67	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Fe_2O_3	5.90	7.39	7.67	7.29	7.14	7.08	7.21	6.89	6.97	6.95	6.96
K_2O	0.14	0.28	0.26	0.24	0.24	0.23	0.23	0.22	0.22	0.22	0.21
Li_2O*	3.57	4.30	4.19	4.11	4.04	3.98	3.92	3.87	3.83	3.80	3.77
MgO	0.12	0.31	0.29	0.31	0.34	0.33	0.32	0.34	0.34	0.30	0.33
MnO	§	0.38	0.34	0.28	0.25	0.23	0.21	0.18	0.16	0.16	0.14
Na_2O	9.58	11.61	11.06	10.49	10.84	10.76	10.70	11.05	10.58	10.20	10.03
NiO	0.40	0.27	0.30	0.30	0.29	0.30	0.32	0.33	0.33	0.33	0.34
P_2O_5	1.05	0.66	0.74	0.85	0.85	0.88	0.90	0.94	0.95	0.97	1.03
PbO	0.41	0.22	0.27	0.28	0.28	0.29	0.33	0.33	0.34	0.35	0.36
SiO_2	27.00	33.27	31.93	31.77	30.76	30.35	29.76	29.10	28.90	28.91	28.61
SO_3	0.20	0.11	0.11	0.12	0.12	0.12	0.12	0.13	0.12	0.11	0.11
SrO	§	0.01	<0.01	0.01	0.01	<0.01	0.01	0.01	0.01	0.01	0.01
TiO_2	0.01	0.67	0.58	0.48	0.44	0.38	0.35	0.29	0.27	0.25	0.22
ZnO	0.08	0.10	0.10	0.10	0.09	0.09	0.10	0.09	0.09	0.09	0.09
ZrO_2	0.39	0.37	0.40	0.41	0.40	0.41	0.43	0.43	0.44	0.46	0.46
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

§ - Not a target constituent
* - Values calculated using the DCP analysis of GBL-G-146A, target concentrations, and simple well-stirred tank model
[#] - Steady-state fluoride concentration from previous tests [2].

Table 4.5. XRF Analyzed Compositions for Glass Discharged During DM100 Melter Test (wt%) (continued).

Test	Plenum Heaters						Dried Feed				
Glass (kg)	Target	294.38	318.1	352.86	381.82	399.34	431.1	462.02	486.3	512.48	545.4
Constituent		HBL-G-14D	HBL-G-15B	HBL-G-17A	HBL-G-17C	HBL-G-17D	HBL-G-40A	HBL-G-41A	HBL-G-42B	HBL-G-44B	HBL-G-48A
Al_2O_3	23.97	22.33	22.37	22.41	22.27	22.39	22.05	22.03	22.16	21.64	21.99
B_2O_3*	19.19	18.02	18.16	18.34	18.47	18.54	18.64	18.73	18.79	18.84	18.90
BaO	0.05	0.07	0.08	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.06
Bi_2O_3	1.14	1.06	1.07	1.09	1.13	1.14	1.08	1.15	1.10	1.08	1.16
CaO	5.58	5.26	5.36	5.38	5.50	5.61	5.36	5.53	5.46	5.38	5.53
CdO	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cr_2O_3	0.52	0.55	0.55	0.55	0.58	0.59	0.55	0.58	0.57	0.56	0.58
F[#]	0.67	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Fe_2O_3	5.90	6.57	6.59	6.56	6.73	6.81	6.32	6.52	6.33	6.21	6.34
K_2O	0.14	0.20	0.21	0.20	0.20	0.21	0.20	0.20	0.20	0.19	0.20
Li_2O*	3.57	3.74	3.72	3.69	3.68	3.67	3.65	3.64	3.63	3.62	3.61
MgO	0.12	0.36	0.34	0.33	0.33	0.31	0.34	0.35	0.36	0.37	0.32
MnO	§	0.13	0.11	0.10	0.09	0.09	0.09	0.08	0.08	0.07	0.06
Na_2O	9.58	10.32	10.24	10.48	10.19	9.87	9.85	9.55	9.82	10.83	9.82
NiO	0.40	0.32	0.33	0.32	0.35	0.34	0.33	0.35	0.34	0.34	0.34
P_2O_5	1.05	1.03	1.05	1.06	1.04	1.06	1.07	1.08	1.09	1.04	1.09
PbO	0.41	0.34	0.35	0.35	0.37	0.39	0.35	0.38	0.37	0.37	0.39
SiO_2	27.00	28.56	28.33	27.95	27.86	27.78	28.98	28.68	28.58	28.31	28.50
SO_3	0.20	0.11	0.11	0.11	0.12	0.11	0.10	0.10	0.11	0.11	0.12
SrO	§	<0.01	0.01	0.01	<0.01	0.01	<0.01	<0.01	0.01	0.01	<0.01
TiO_2	0.01	0.20	0.17	0.15	0.14	0.13	0.12	0.11	0.10	0.10	0.09
ZnO	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
ZrO_2	0.39	0.44	0.46	0.45	0.49	0.49	0.45	0.48	0.46	0.46	0.50
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

§ - Not a target constituent
* - Target values calculated using the DCP analysis of GBL-G-146A, target concentrations, and simple well-stirred tank model
[#] - Steady-state fluoride concentration from previous tests [2]

Table 4.5. XRF Analyzed Compositions for Glass Discharged During DM100 Melter Test (wt%) (continued).

Test	Dried Feed											
Glass (kg)	Target	571.84	593.66	619.42	641.24	675.72	707.94	731.94	761	785.72	815.78	571.84 - 815.78
Constituent		HBL-G-49A	HBL-G-49C	HBL-G-50B	HBL-G-50D	HBL-G-55A	HBL-G-56B	HBL-G-57B	HBL-G-57D	HBL-G-59B	HBL-G-59D	% Dev
Al_2O_3	23.97	22.17	21.95	22.15	22.13	22.25	22.09	22.13	22.12	22.29	22.52	-7.48
B_2O_3*	19.19	18.94	18.97	19.00	19.02	19.05	19.07	19.09	19.10	19.12	19.13	NC
BaO	0.05	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.06	0.07	0.07	NC
Bi_2O_3	1.14	1.11	1.21	1.16	1.18	1.11	1.20	1.22	1.21	1.12	1.10	1.72
CaO	5.58	5.48	5.70	5.57	5.59	5.48	5.65	5.72	5.65	5.47	5.44	-0.13
CdO	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NC
Cr_2O_3	0.52	0.58	0.59	0.58	0.57	0.56	0.57	0.59	0.59	0.56	0.54	NC
F[#]	0.67	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	NC
Fe_2O_3	5.90	6.16	6.55	6.26	6.28	6.09	6.34	6.44	6.39	5.99	5.89	5.74
K_2O	0.14	0.20	0.20	0.19	0.20	0.19	0.20	0.19	0.19	0.19	0.19	NC
Li_2O*	3.57	3.61	3.60	3.60	3.60	3.59	3.59	3.59	3.58	3.58	3.58	NC
MgO	0.12	0.35	0.32	0.34	0.34	0.33	0.34	0.35	0.34	0.35	0.32	NC
MnO	§	0.05	0.06	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	NC
Na_2O	9.58	9.94	9.57	9.88	9.84	9.87	9.81	9.41	9.65	10.02	9.79	2.06
NiO	0.40	0.33	0.35	0.33	0.33	0.33	0.34	0.35	0.35	0.33	0.32	NC
P_2O_5	1.05	1.09	1.09	1.10	1.09	1.12	1.11	1.12	1.11	1.13	1.11	5.21
PbO	0.41	0.38	0.40	0.39	0.39	0.37	0.40	0.41	0.40	0.38	0.36	NC
SiO_2	27.00	28.49	28.29	28.27	28.25	28.51	28.10	28.21	28.14	28.32	28.58	4.86
SO_3	0.20	0.12	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.12	0.12	NC
SrO	§	0.01	0.01	<0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01	NC
TiO_2	0.01	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.05	NC
ZnO	0.08	0.08	0.09	0.08	0.08	0.08	0.09	0.09	0.09	0.08	0.08	NC
ZrO_2	0.39	0.47	0.50	0.49	0.50	0.47	0.51	0.52	0.50	0.48	0.47	NC
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	NC

§ - Not a target constituent
* - Target values calculated using the DCP analysis of GBL-G-146A, target concentrations, and simple well-stirred tank model
[#] - Steady-state fluoride concentration from previous tests [2].
NC – Not calculated

Table 5.1. Results from DM100 Off-Gas Emission Samples.

		Plenum Heaters				Dried Feed			
		9/1/2010 12:53 – 13:53 21.2% Moisture, 98.6% Isokinetic				9/9/2010 21:29 – 22:29 13.9% Moisture, 103% Isokinetic			
		Feed[#] (mg/min)	Output (mg/min)	% Emitted	DF	Feed[#] (mg/min)	Output (mg/min)	% Emitted	DF
Particulate	Total[$]	218600	504	0.23	434	282900	395	0.14	717
	Al	21874	13.99	0.06	1564	28531	15.0	0.05	1906
	Bi	882	6.49	0.74	136	1150	6.38	0.55	180
	B	10273	25.09	0.24	410	13400	27.5	0.21	487
	Ba	77.2	0.15	0.19	521	101	0.16	0.16	643
	Ca	6880	6.27	0.09	1098	8974	6.82	0.08	1315
	Cd	15.2	0.59	3.88	25.8	6.1	0.35	5.69	17.6
	Cr	614	6.44	1.05	95.4	801	5.36	0.67	149
	F*	1156	19.4	1.68	59.6	1508	17.3	1.15	87.2
	Fe	7117	14.75	0.21	482	9283	15.5	0.17	601
	K	200	2.93	1.46	68.5	261	2.74	1.05	95.4
	Li	2861	10.23	0.36	280	3731	8.90	0.24	419
	Mg	125	0.86	0.69	145	163	0.85	0.52	193
	Na	12261	52.96	0.43	232	15992	50.7	0.32	316
	Ni	542	0.69	0.13	785	707	0.79	0.11	898
	P	791	3.44	0.43	230	1032	< 0.10	< 0.01	> 10315
	Pb	657	3.93	0.60	167	856	4.54	0.53	189
	S*	138	49.1	35.6	2.8	180	49.9	27.7	3.6
	Si	21772	15.11	0.07	1441	28399	15.5	0.05	1837
	Ti	10.3	0.12	1.14	87.7	13.5	0.22	1.61	62.0
	Zn	111	0.26	0.24	419	145	0.27	0.19	532
	Zr	498	0.41	0.08	1204	650	0.44	0.07	1471
Gas	B	10273	157	1.53	65.3	13400	38.7	0.29	346
	F	1156	290	25.1	4.0	1508	115	7.61	13.1
	S	138	37.3	27.0	3.7	180	18.0	9.98	10.0

[$] - From gravimetric analysis of filters and particulate nitric acid rinses
[#] - Feed rate calculated from target composition and total glass production rate
* - Calculated from analysis of filter particulate by water dissolution

Table 5.1. Results from DM100 Off-Gas Emission Samples (continued).

		Baseline at 1200 °C [2]				Baseline at 1150 °C [2]			
		6/24/08 19:44 – 20:44 98.5% Isokinetic, 14.6% Moisture				06/27/08 17:26 – 18:26 103.5% Isokinetic, 10.4% Moisture			
		Feed Rate[#] (mg/min)	Emissions Rate (mg/min)	% Feed	DF	Feed Rate[#] (mg/min)	Emissions Rate (mg/min)	% Feed	DF
Particulate	Total[$]	138200	171	0.12	806	87500	45.2	0.05	1938
	Al	14266	13.8	0.10	1038	9035	2.77	0.03	3261
	B	6700	8.58	0.13	781	4243	1.99	0.05	2127
	Ba	50	< 0.10	< 0.20	> 504	32	< 0.10	< 0.31	> 319
	Bi	575	2.56	0.44	225	364	0.50	0.14	726
	Ca	4487	2.42	0.05	1852	2842	0.47	0.02	6086
	Cd	20	0.14	0.71	141	13	< 0.10	< 0.78	> 128
	Cl*	0	0.21	NC	NC	0	8.79	NC	NC
	Cr	400	1.94	0.48	207	254	0.77	0.30	329
	F*	754	19.3	2.56	39.1	477	5.53	1.16	86.3
	Fe	4641	4.09	0.09	1136	2939	0.91	0.03	3235
	K	131	1.19	0.91	110	83	0.40	0.48	208
	Li	1866	3.48	0.19	537	1182	1.11	0.09	1065
	Mg	81	0.22	0.27	369	52	< 0.10	< 0.19	> 516
	Na	7996	20.1	0.25	399	5064	7.38	0.15	686
	Ni	354	0.29	0.08	1219	224	< 0.10	< 0.04	> 2240
	P	516	0.41	0.08	1258	327	0.38	0.12	857
	Pb	428	1.08	0.25	395	271	0.39	0.14	701
	S*	90	4.41	4.90	20.4	57	1.60	2.81	35.6
	Si	14199	6.42	0.05	2211	8993	1.56	0.02	5776
	Zn	72	0.10	0.14	700	46	< 0.10	< 0.22	> 458
	Zr	325	0.15	0.05	2209	206	< 0.10	< 0.05	> 2057
Gas	B	6700	55.2	0.82	121	4243	24.1	0.57	176
	Cl	0	14.8	NC	NC	0	8.76	NC	NC
	F	754	175	23.2	4.3	477	99.9	20.9	4.8
	S	90	40.9	45.4	2.2	57	15.4	27.0	3.7

[$] - From gravimetric analysis of filters and particulate nitric acid rinses
[#] - Feed rate calculated from target composition and steady state production rate
* - Calculated from direct analysis of nitric acid rinses
NC – Not Calculated

Table 5.2. Concentrations (ppmv) of Selected Species in DM100 Exhaust Measured by FTIR Spectroscopy.

	Baseline 1150 °C		**Baseline 1200 °C**		**Plenum Heaters 1200 °C**		**Dried Feed 1200 °C**	
	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
N_2O	<1.0	<1.0 – 2.9	<1.0	<1.0 - 2.8	<1.0	<1.0 – 1.5	<1.0	<1.0 – 2.9
NO	55.4	2.2 - 282	86.8	36.7 - 307	145	24.1 – 210	197	<1.0 – 447
NO_2	5.4	<1.0 - 52.5	6.9	<1.0 - 51.7	12.6	<1.0 – 35.5	30.5	<1.0 – 139
NH_3	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
H_2O [%]	5.6	1.5 - 14.6	7.5	3.6 - 16.9	10.6	1.9 – 13.6	7.4	0.7 – 20.1
CO_2	1336	369 - 5208	1836	922 - 5169	2570	783 - 3899	2417	366 - 6214
Nitrous Acid	<1.0	NA	<1.0	NA	<1.0	<1.0 – 1.7	<1.0	<1.0 – 1.3
Nitric Acid	<1.0	NA	<1.0	NA	3.2	<1.0 – 78.0	3.1	<1.0 – 15.4
HCN	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
SO_2	3.6	<1.0 - 16.5	6.0	1.1 - 14.2	1.3	<1.0 – 8.0	7.2	<1.0 – 12.5
CO	<1.0	<1.0 - 3.1	<1.0	<1.0 - 3.2	<1.0	<1.0 – 2.2	1.8	<1.0 – 8.5
HCl	<1.0	<1.0 - 1.4	1.5	1.5 - 3.0	3.0	<1.0 – 39.8	6.0	<1.0 – 13.1
HF	23.9	17.9 - 34.0	29.3	9.5 - 41.9	13.6	<1.0 –48.9	37.0	6.1 – 63.5

NA : Not applicable.

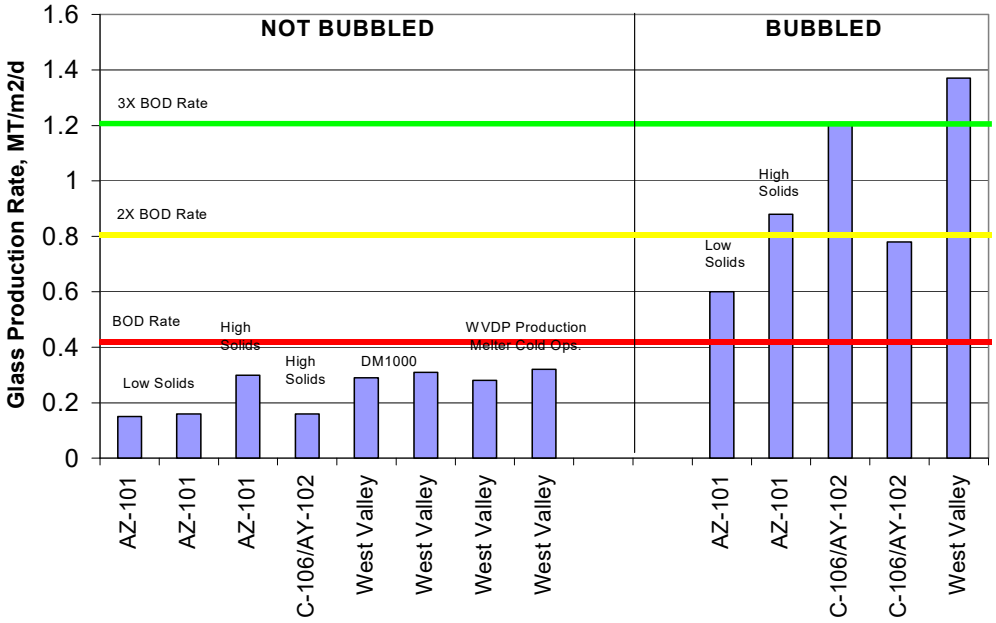

Figure 1.1. Comparison of glass production rates for Hanford WTP (AZ101, C106/AY102) and West Valley HLW feeds with and without bubbling determined on the DM1000 melter (1.2 m^2). The DM1000 rates for West Valley feed without bubbling compares well to those obtained during WVDP cold commissioning runs.

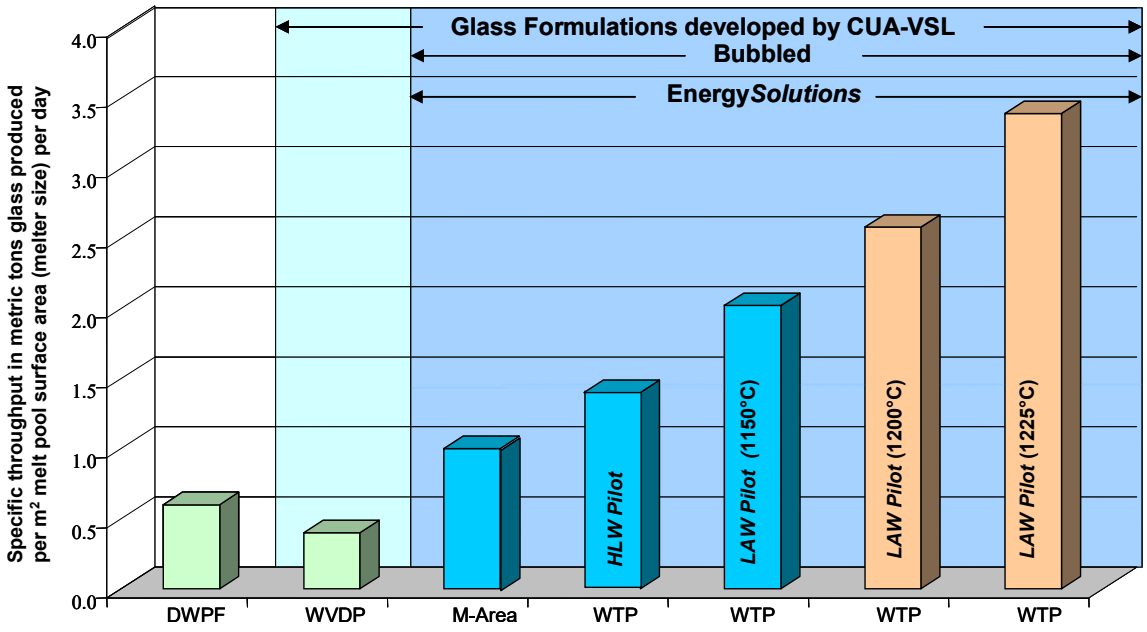

Figure 1.2. Comparison of glass production rates with conventional (DWPF and WVDP) and bubbled JHCMs and further enhancements demonstrated by combining modest operating temperature increases with bubbling. Note: Bubblers have recently been installed in the DWPF melter resulting in a near doubling of the production rate.

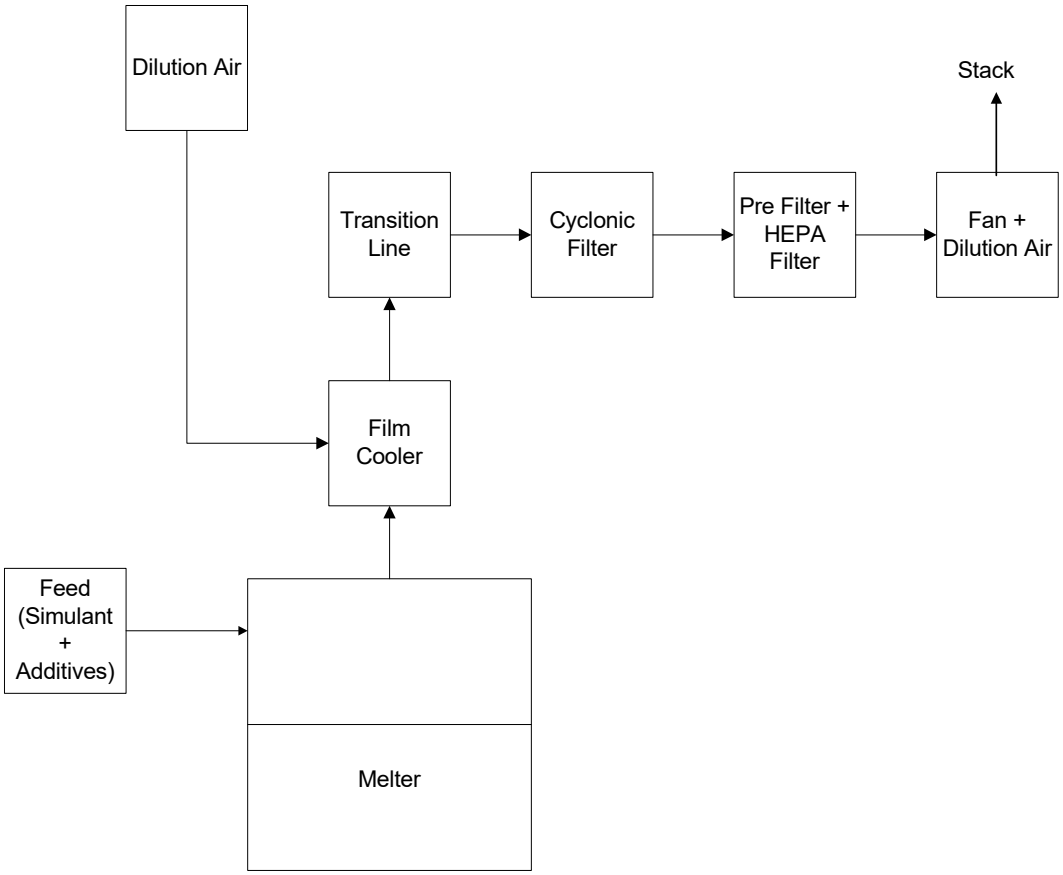

Figure 1.3. Schematic diagram of DuraMelter 100 vitrification system.

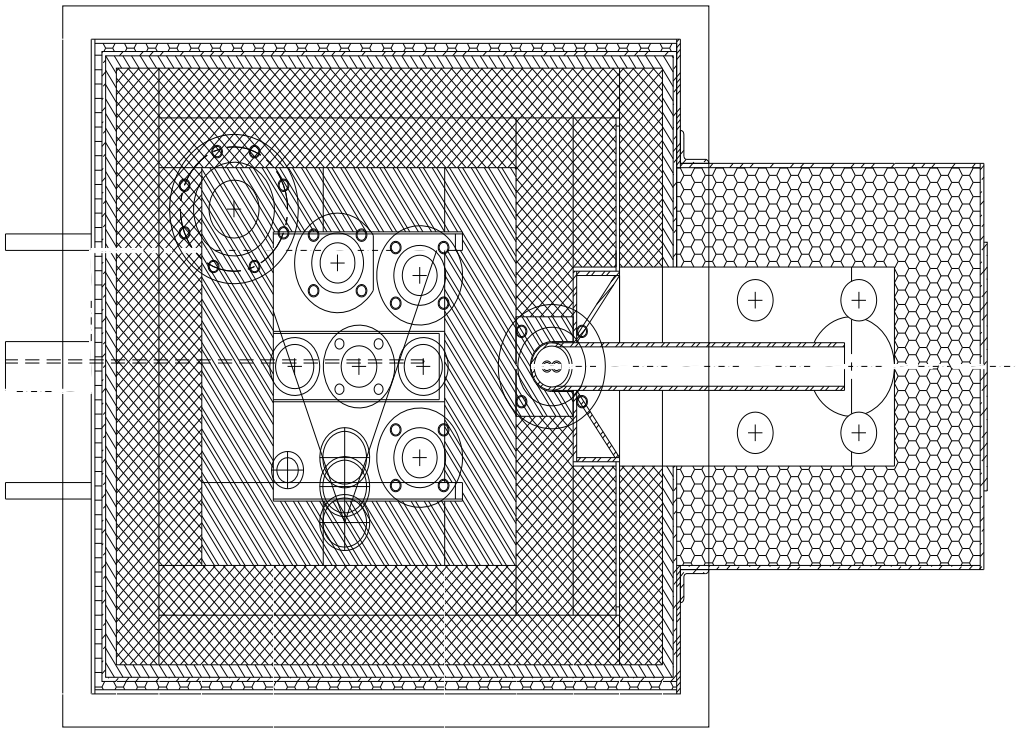

Figure 1.4.a. Schematic diagram showing cross-section through the DM100-BL-melter. Plan view showing locations of lid ports.

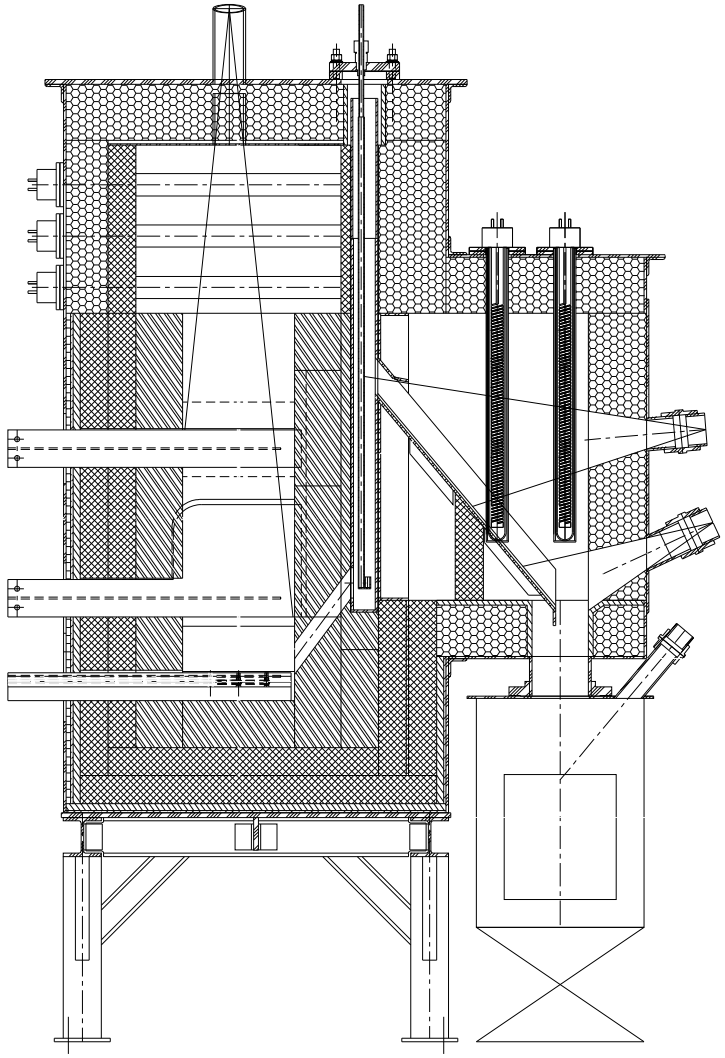

Figure 1.4.b. Schematic diagram showing cross-section through the DM100-BL melter.

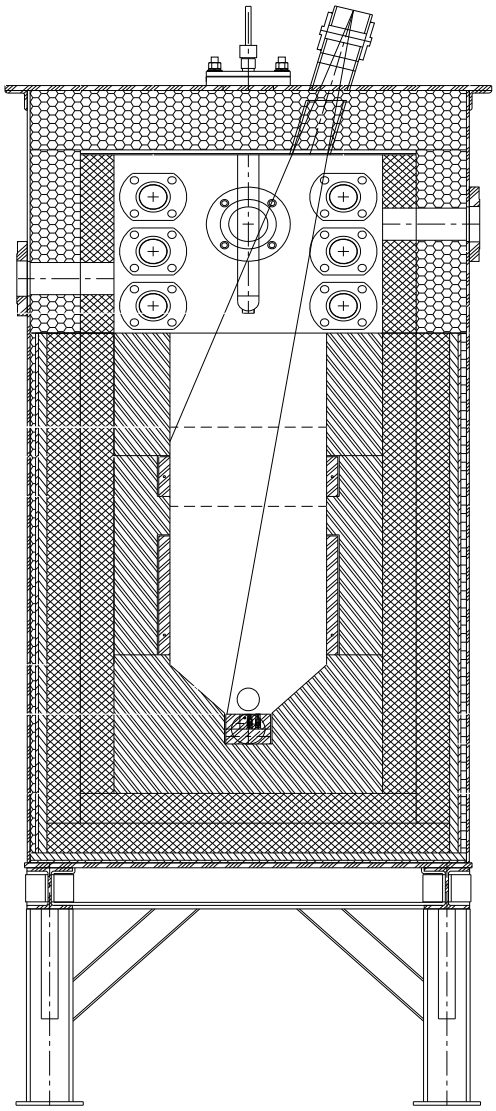

Figure 1.4.c. Schematic diagram showing cross-section through the DM100-BL melter.

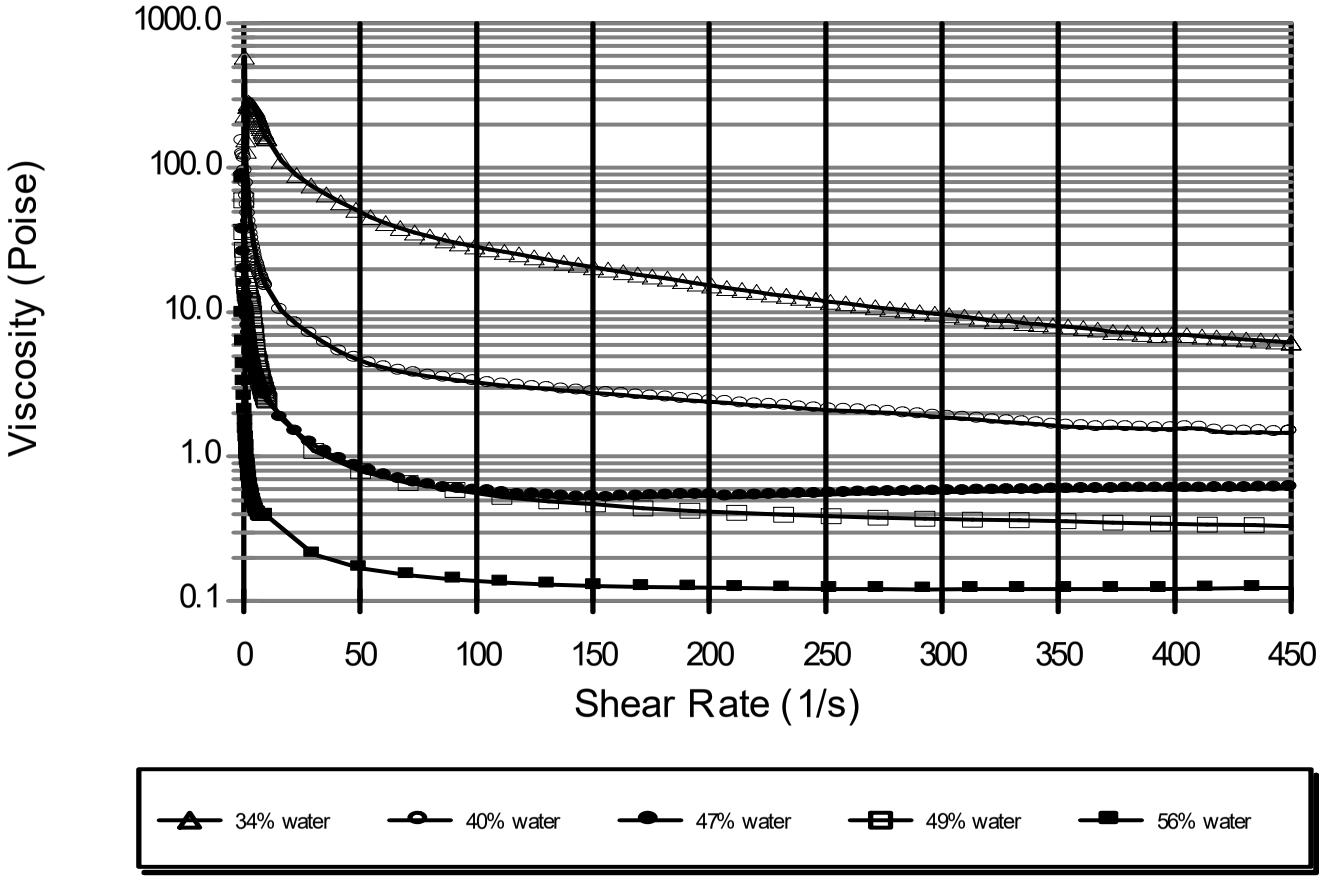

Figure 2.1. Viscosity versus shear rate at various feed water contents.

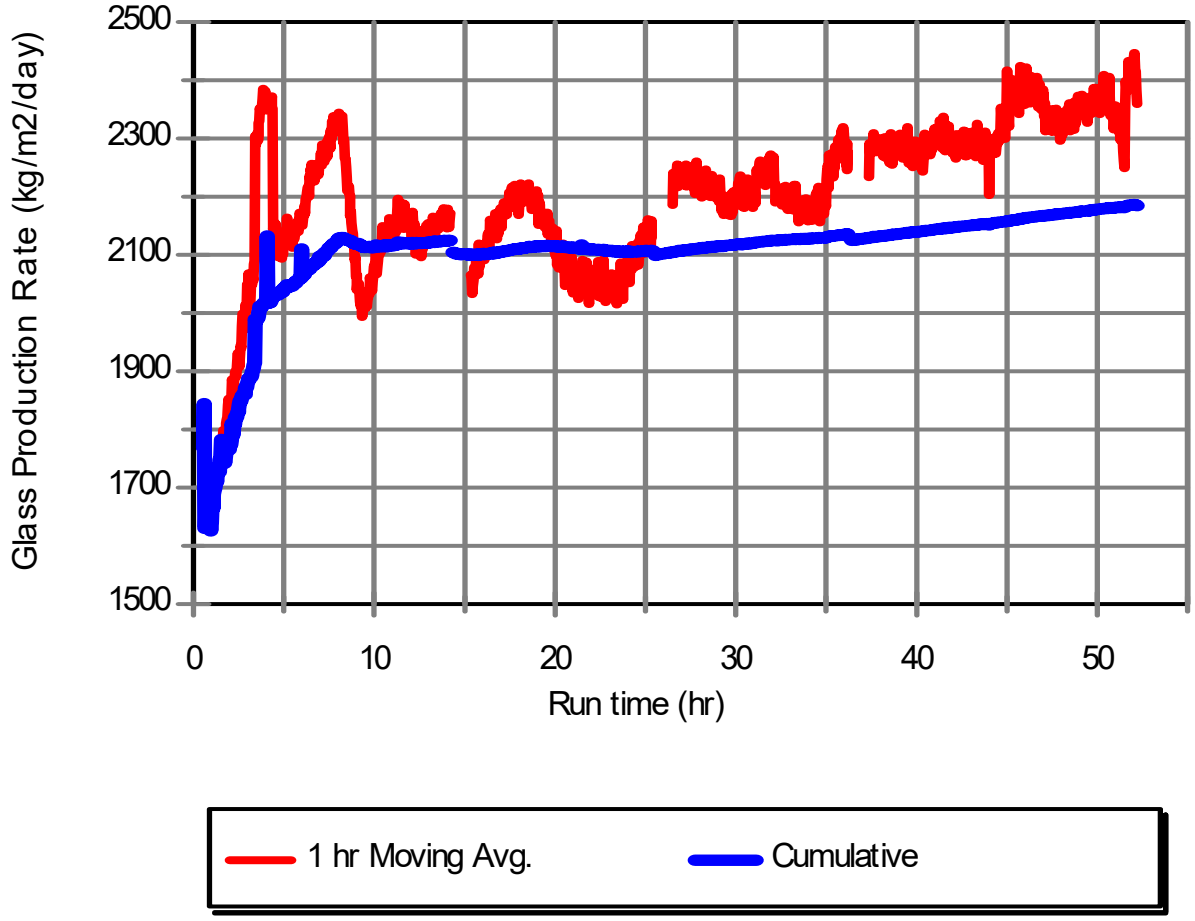

Figure 3.1.a. Glass production rates (hourly moving averages and cumulative) for DM100 test using plenum heaters.

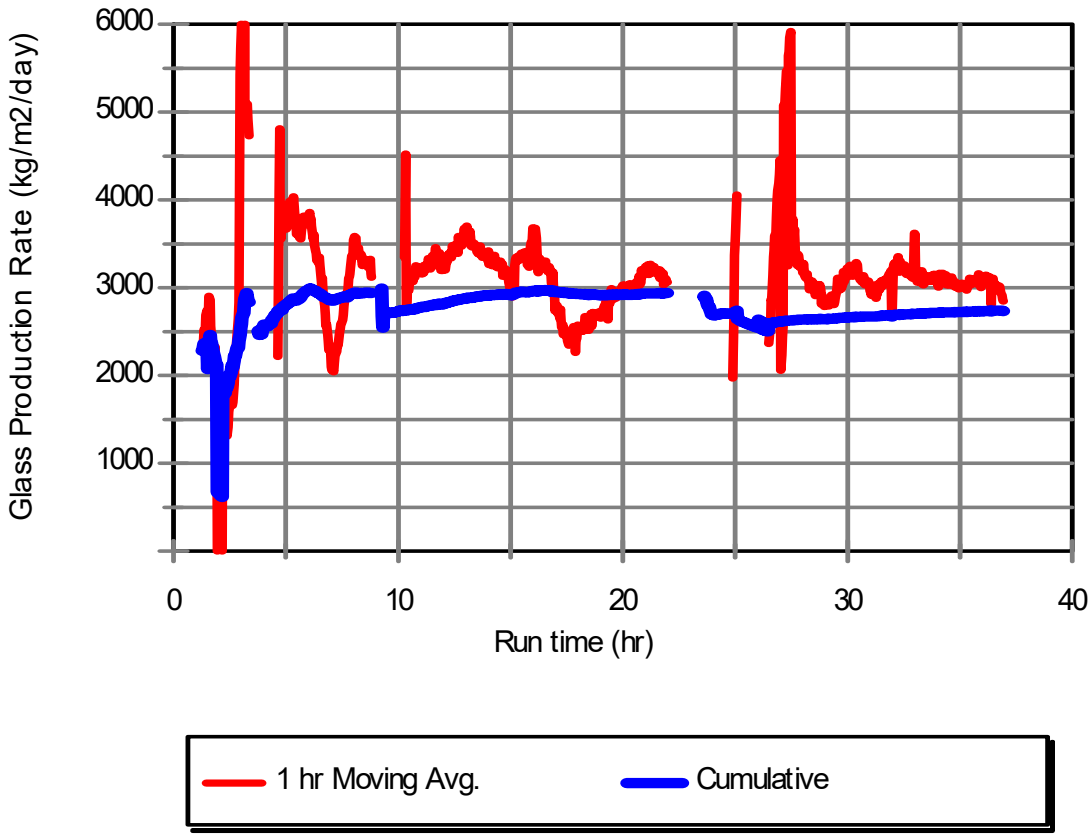

Figure 3.1.b. Glass production rates (hourly moving averages and cumulative) for DM100 test with dried feed.

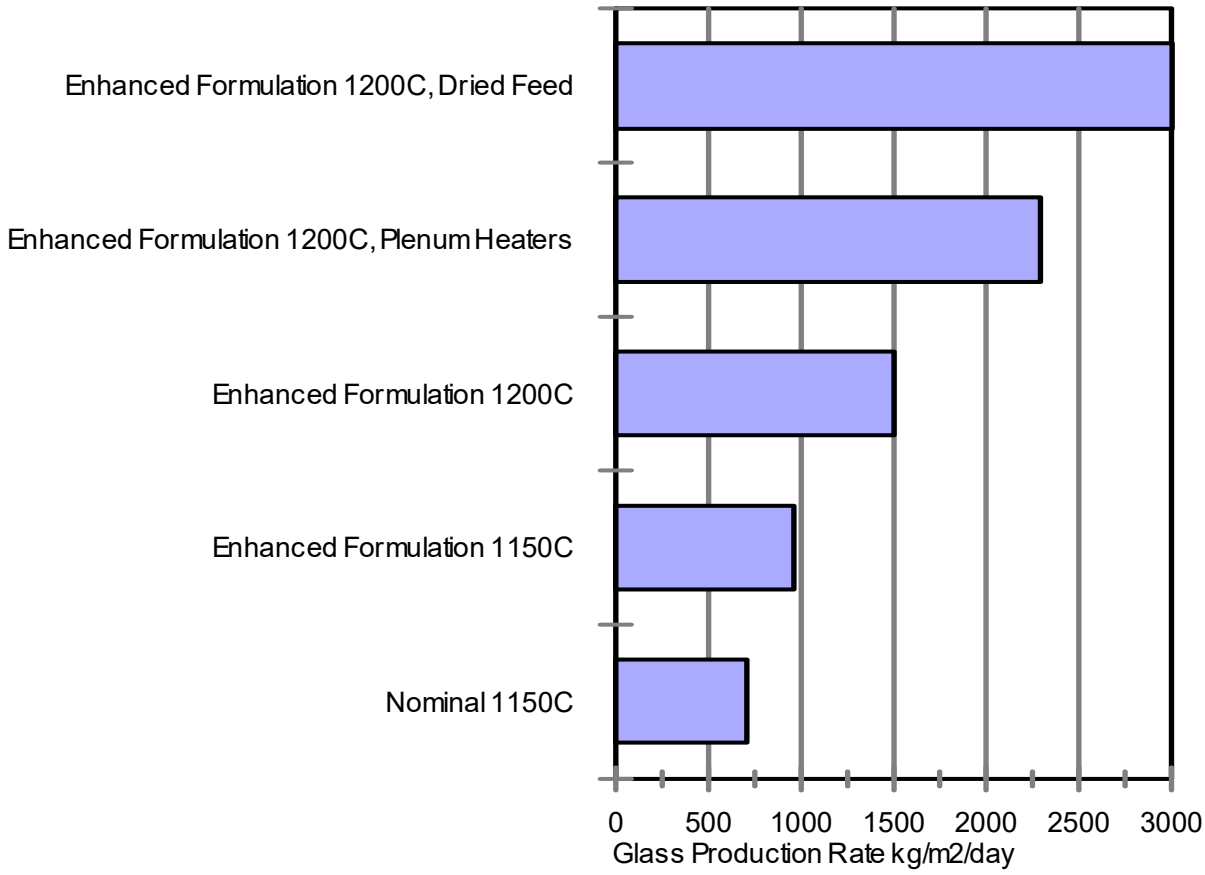

Figure 3.2. Steady-state glass production rates during DM100 tests with high aluminum Hanford waste using "nominal" [1] and "enhanced" [2, 3] glass formulations.

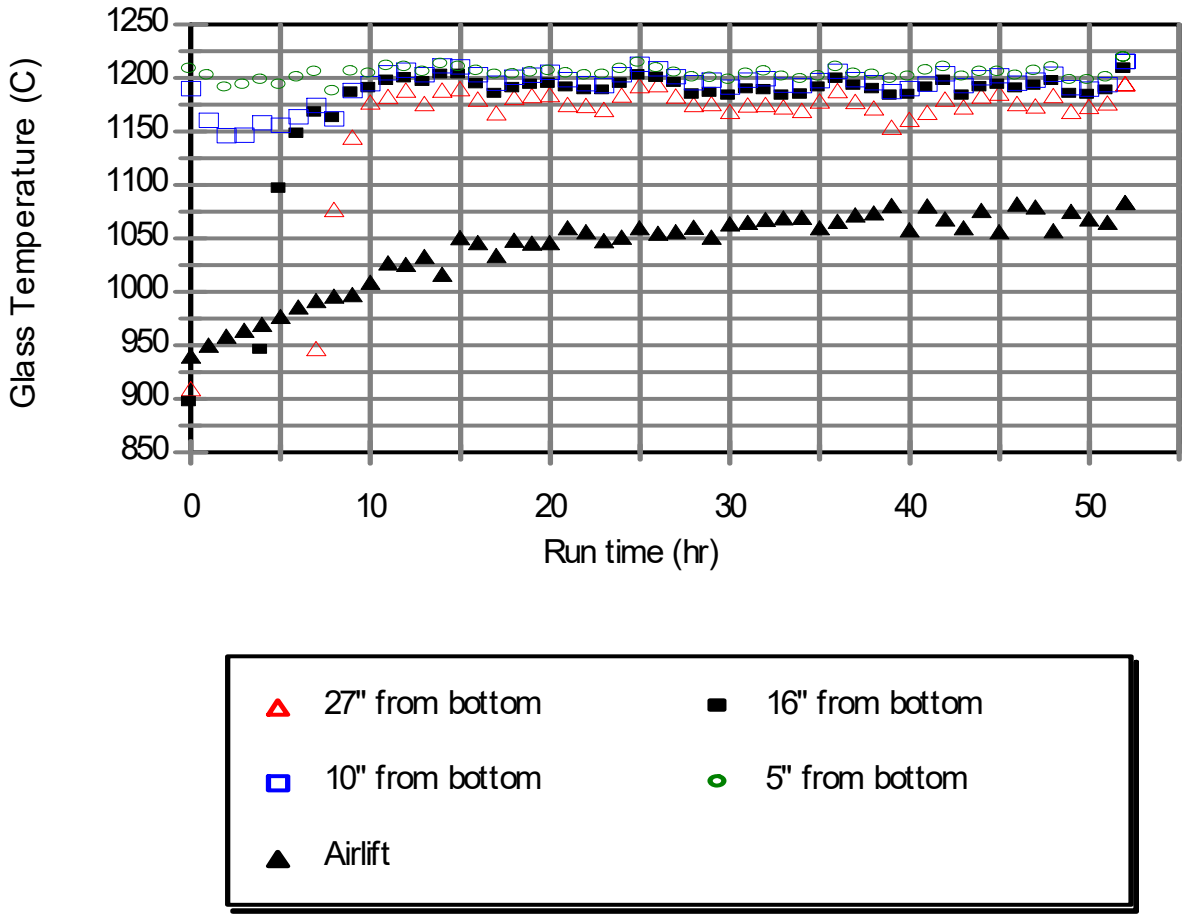

Figure 3.3.a. Glass temperatures (hourly averages) during DM100 test with plenum heaters.

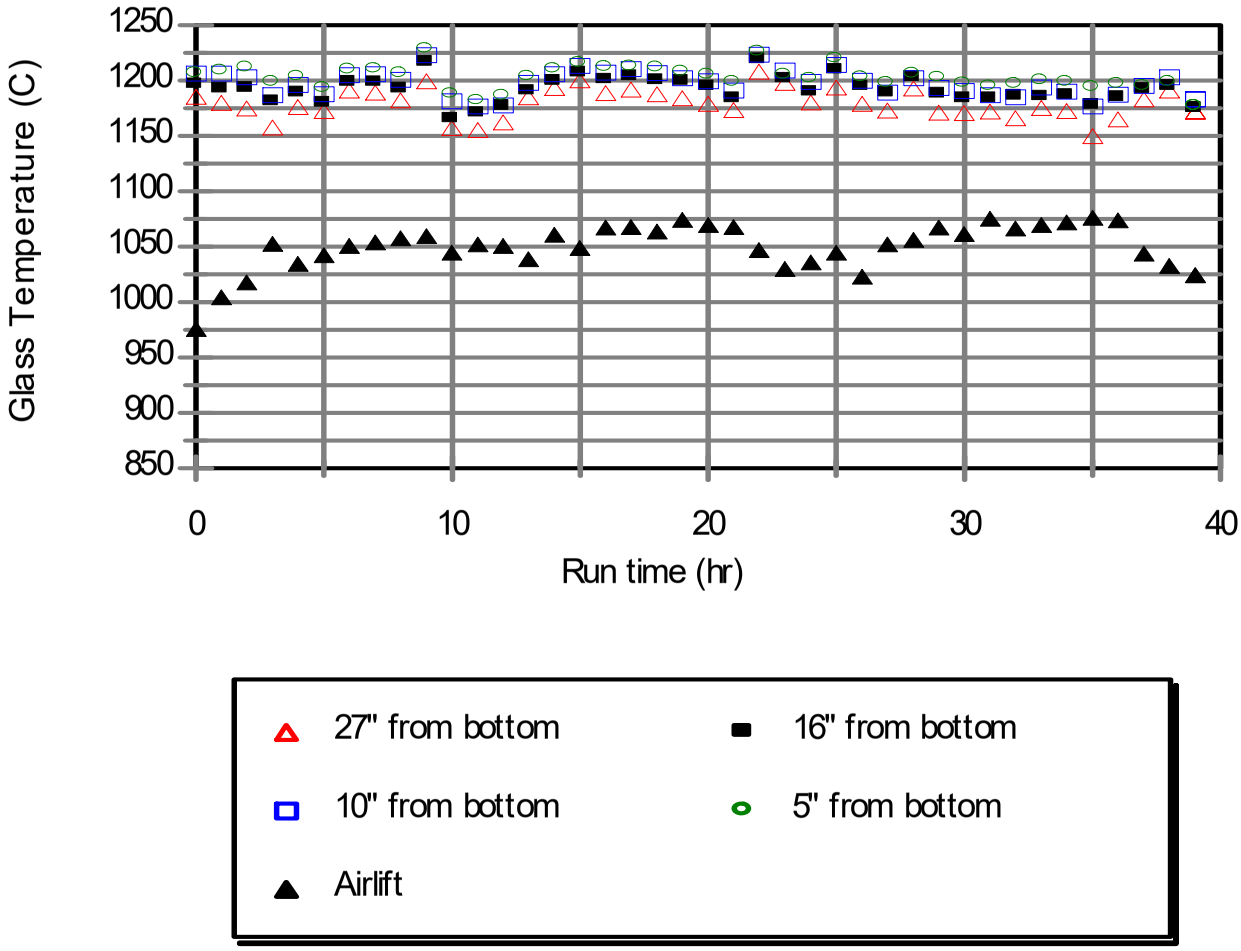

Figure 3.3.b. Glass temperatures (hourly averages) during DM100 Test with dried feed.

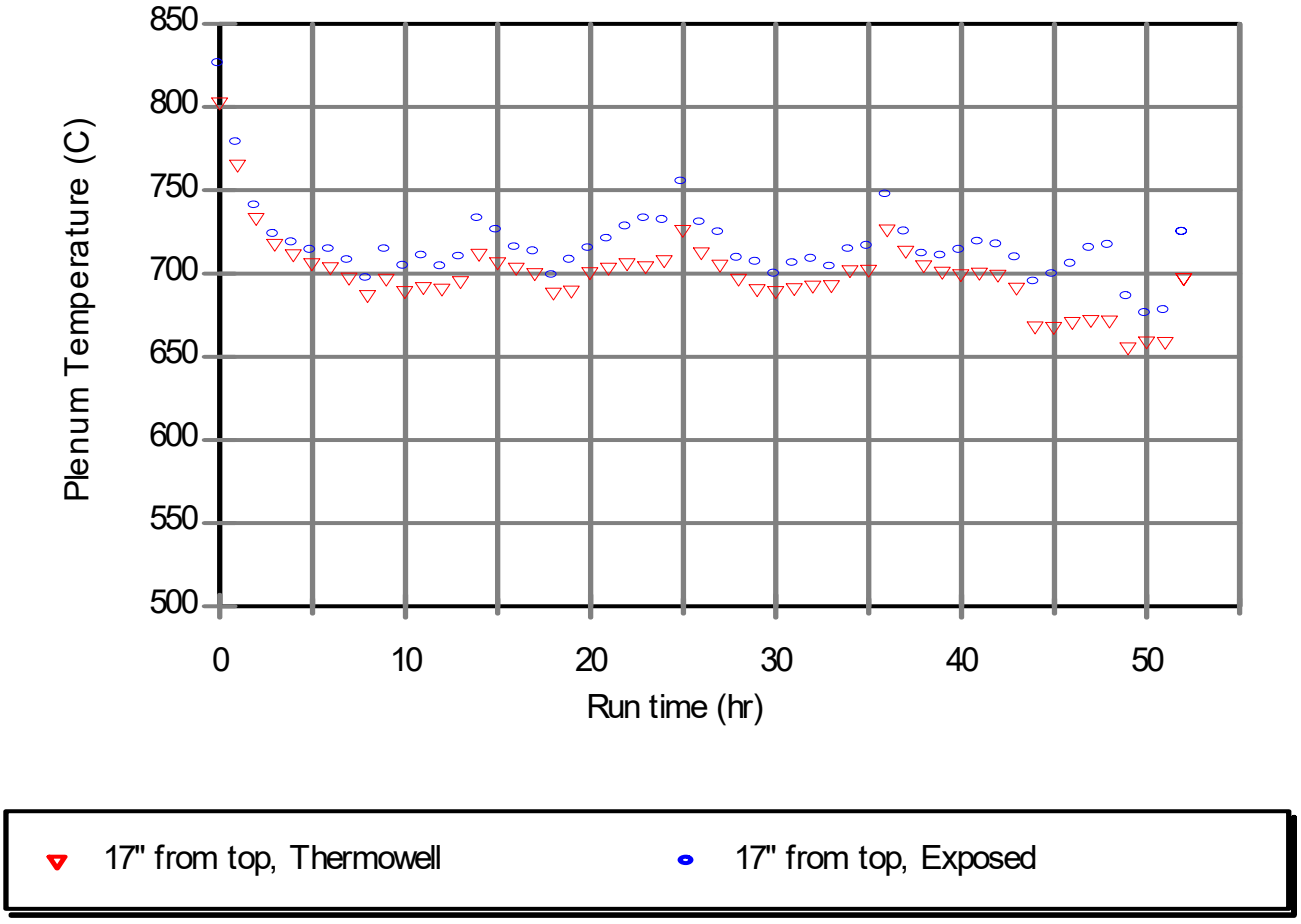

Figure 3.4.a. Plenum temperatures (hourly averages) during DM100 test with plenum heaters.

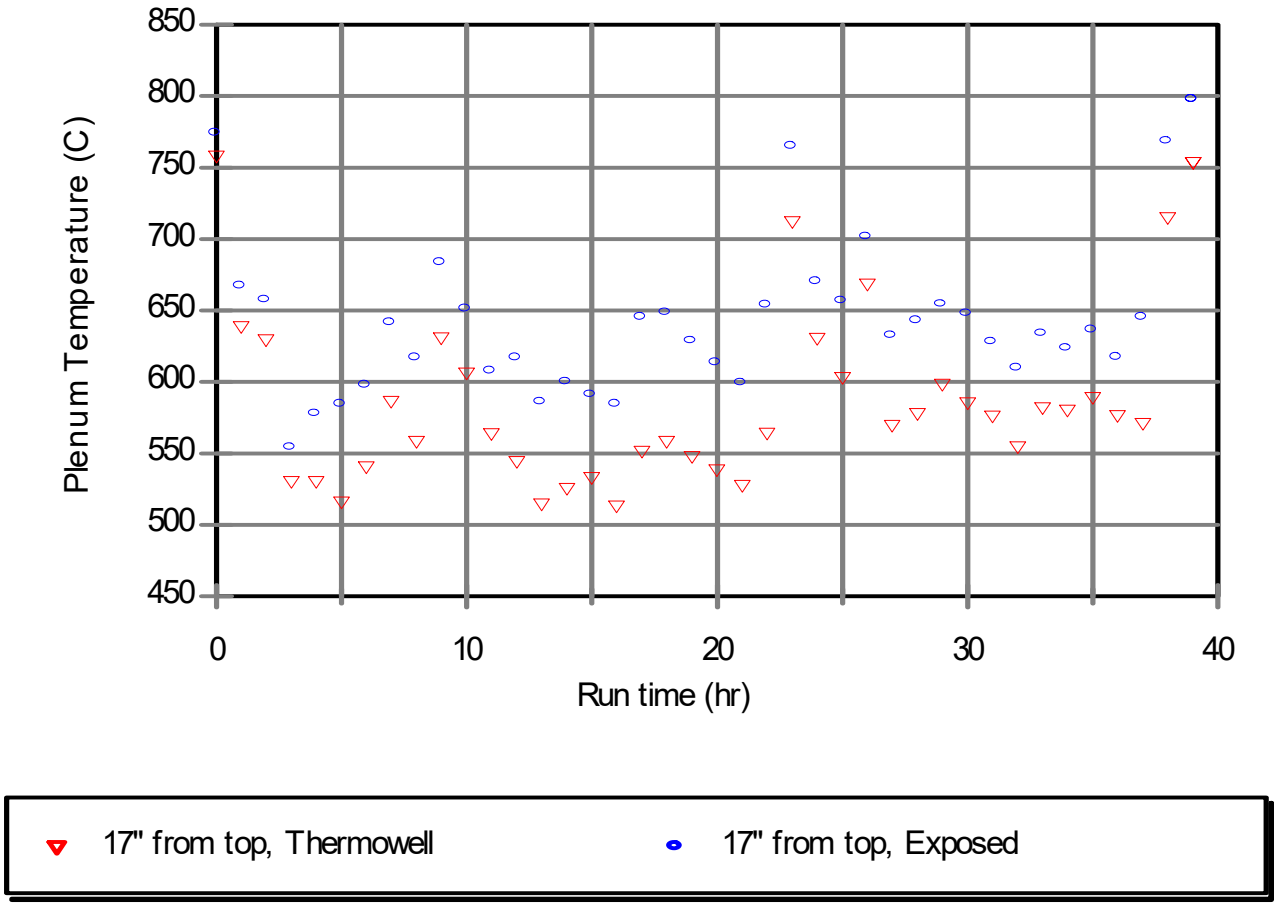

Figure 3.4.b. Plenum temperatures (hourly averages) during DM100 test with dried feed.

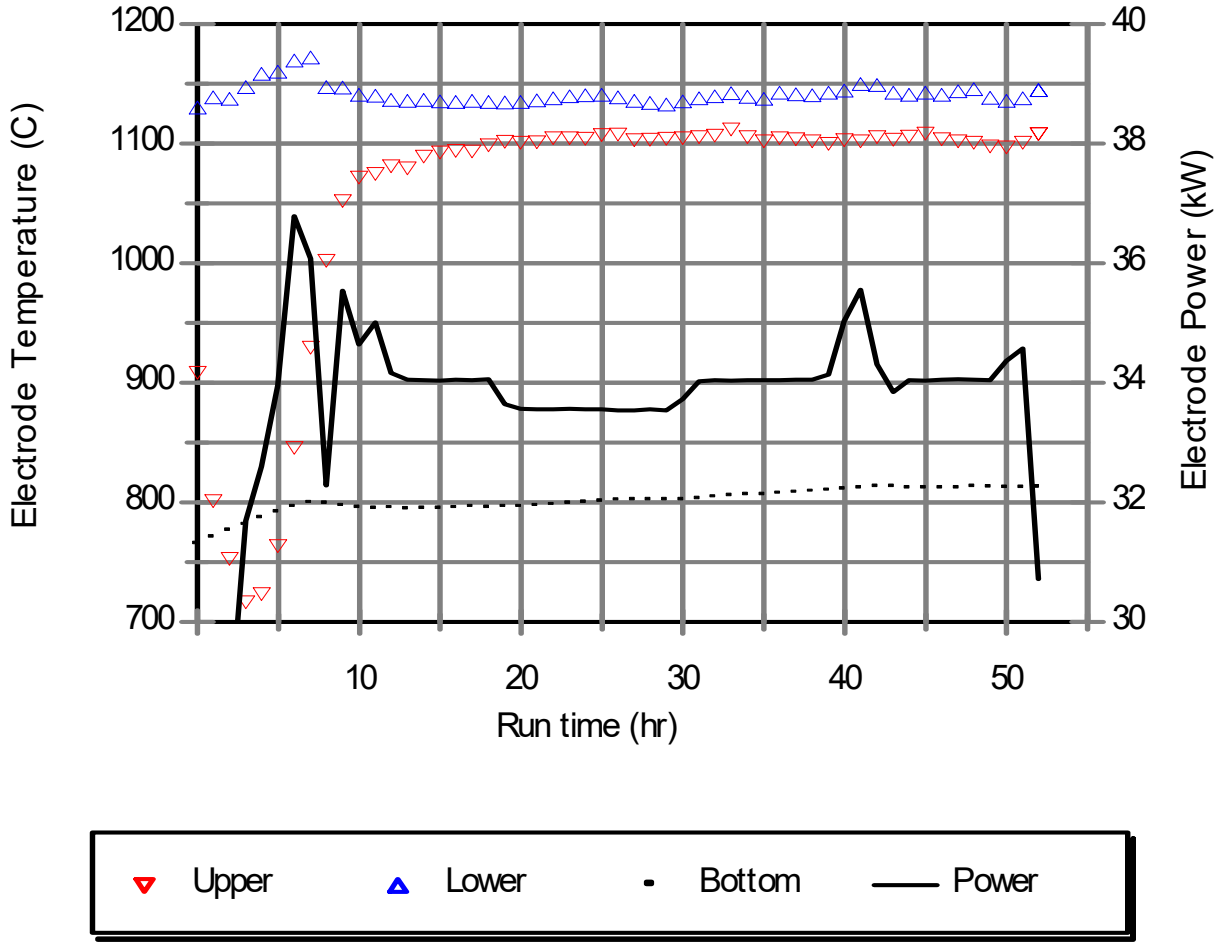

Figure 3.5.a. Electrode temperatures and power (hourly averages) during DM100 test with plenum heaters.

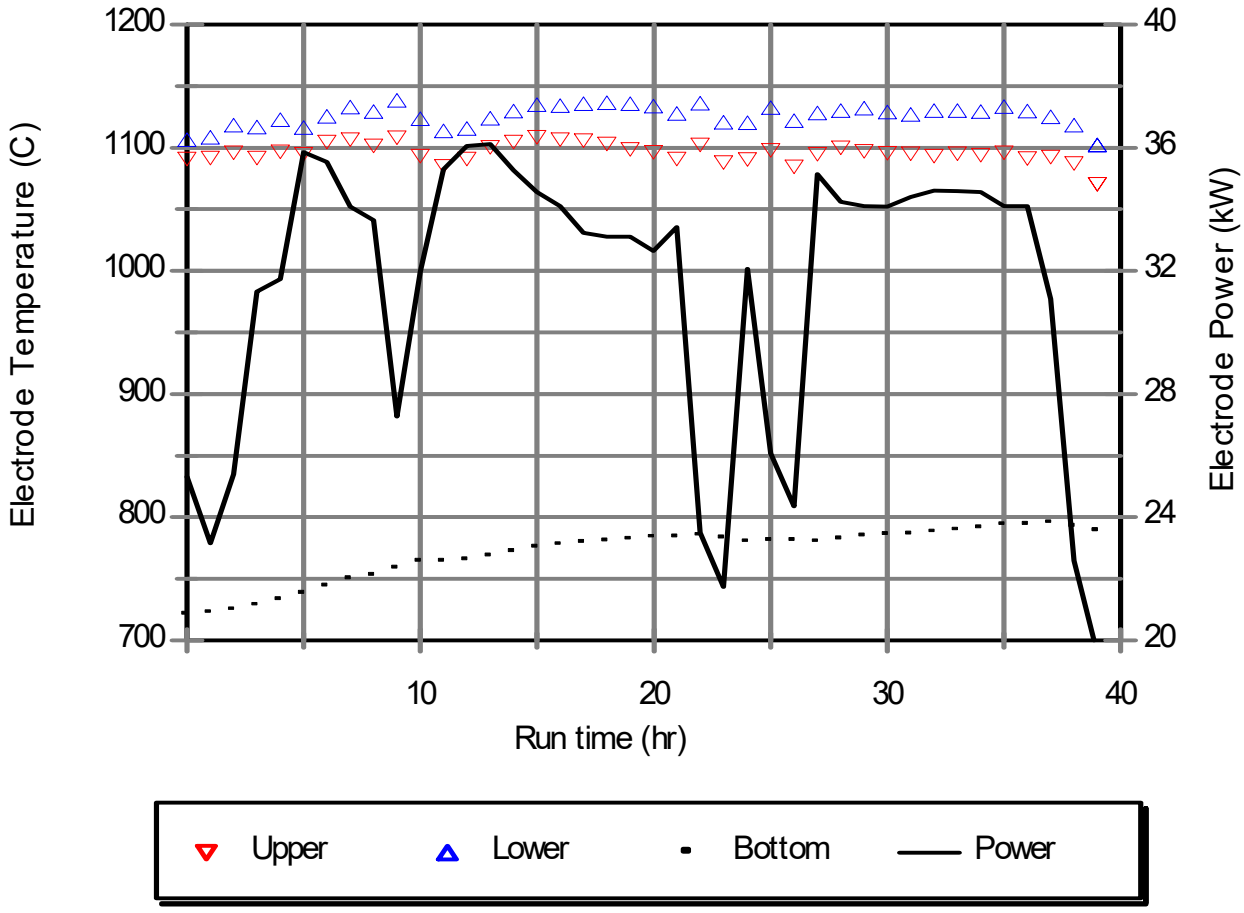

Figure 3.5.b. Electrode temperatures and power (hourly averages) during DM100 test with dried feed.

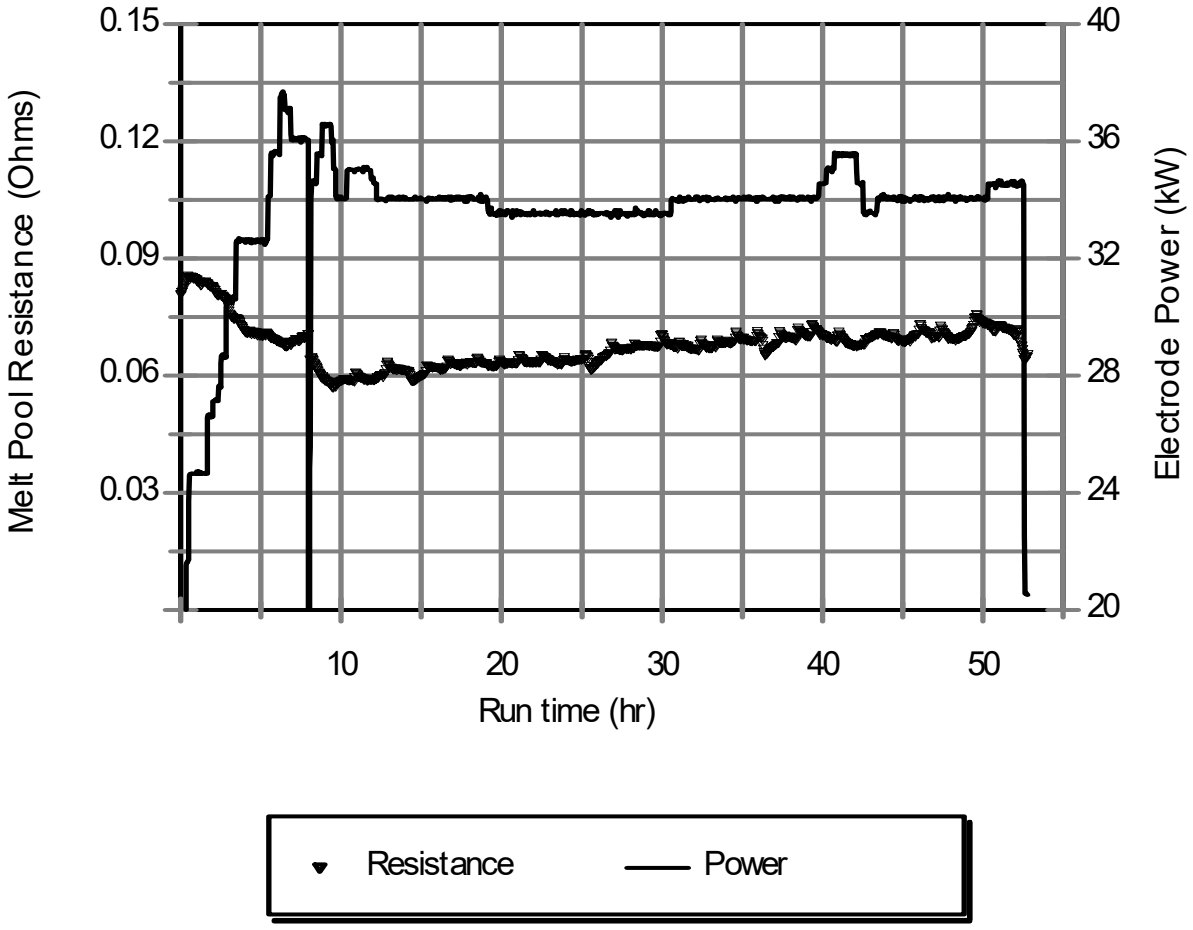

Figure 3.6.a. Melt pool resistance and total electrode power during DM100 test with plenum heaters.

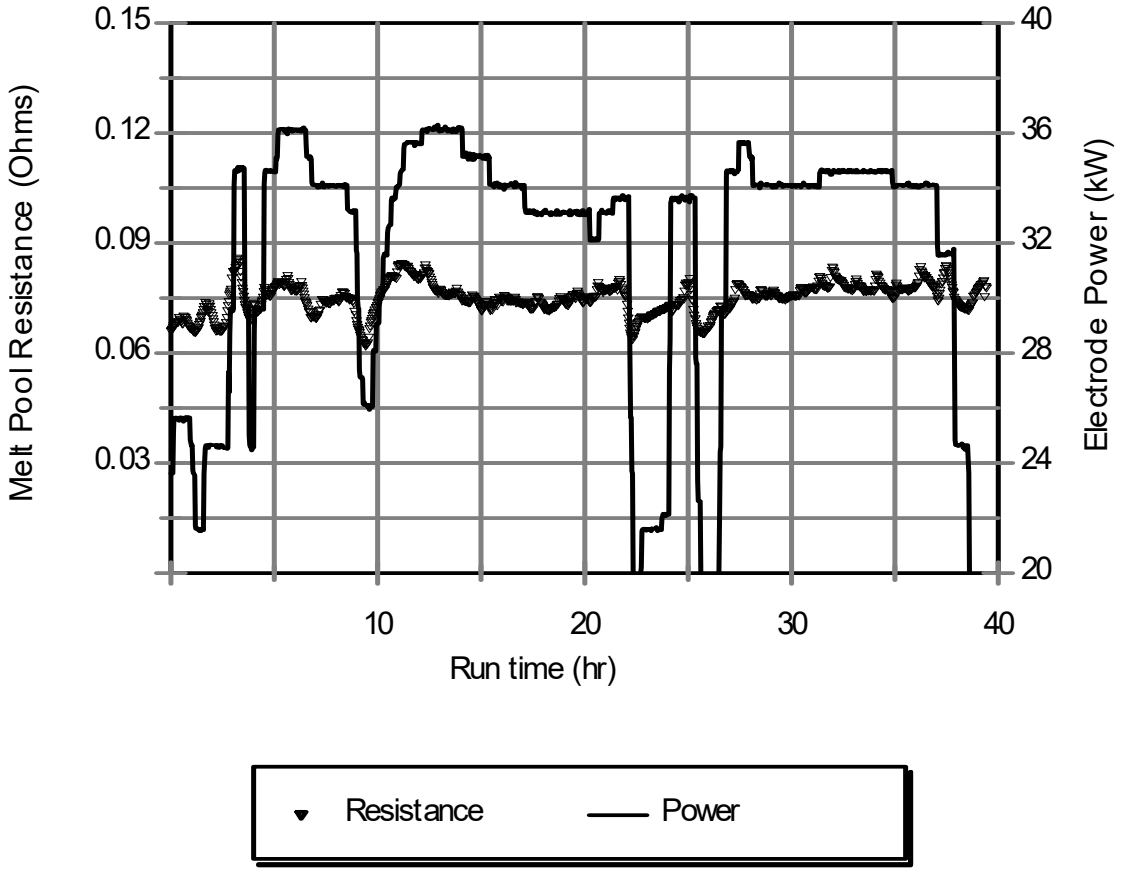

Figure 3.6.b. Melt pool resistance and total electrode power during DM100 test with dried feed.

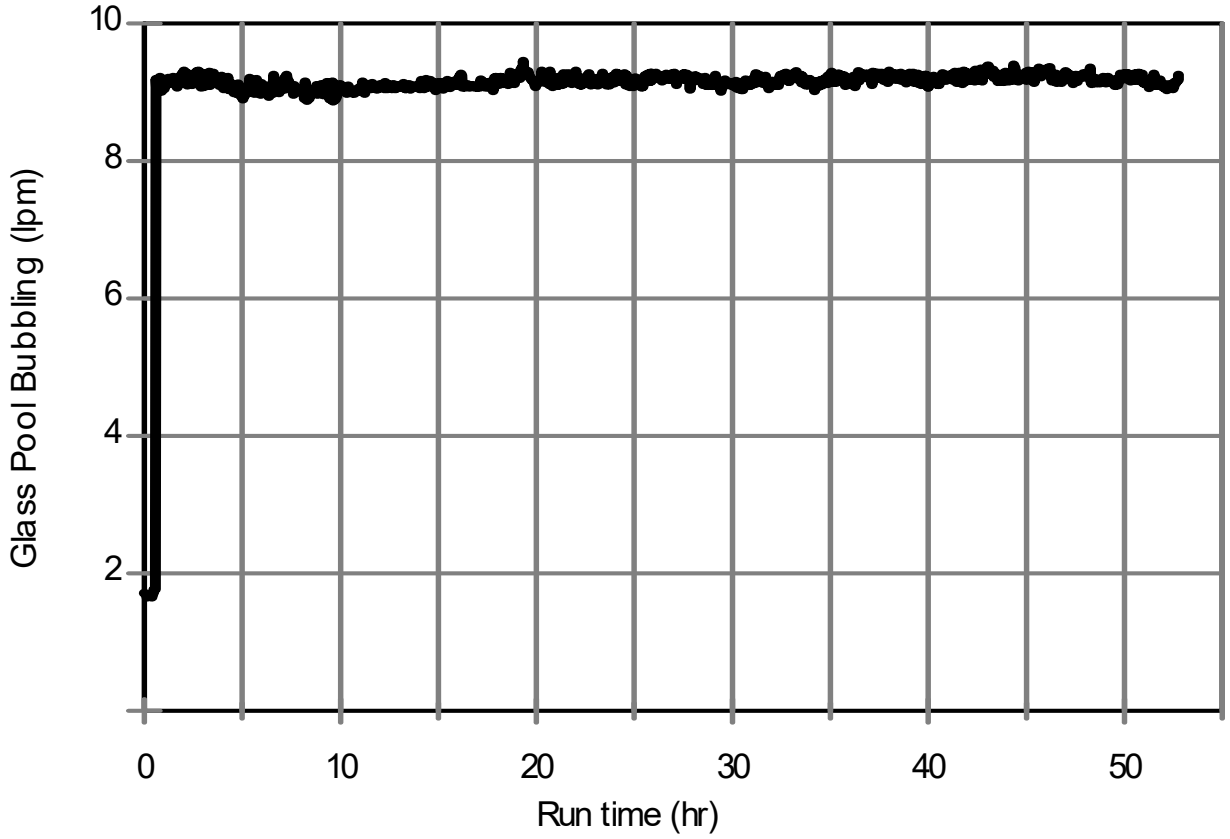

Figure 3.7.a. Melt pool bubbling during DM100 test with plenum heaters.

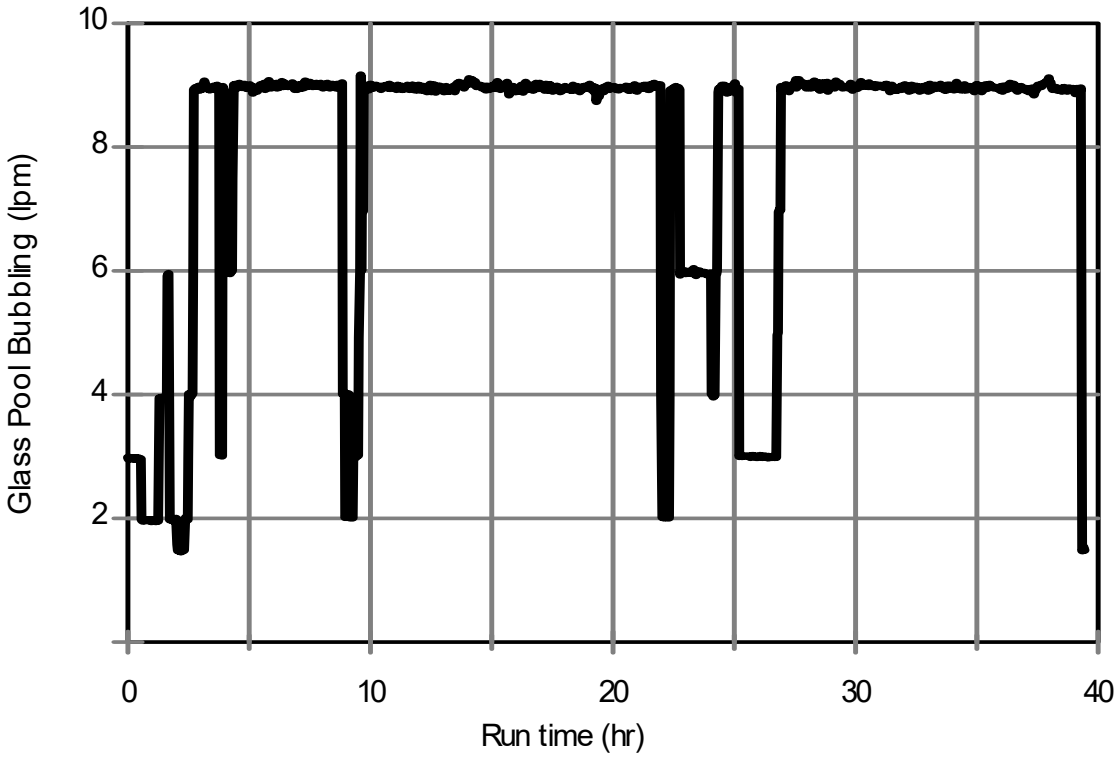

Figure 3.7.b. Melt pool bubbling during DM100 test with dried feed.

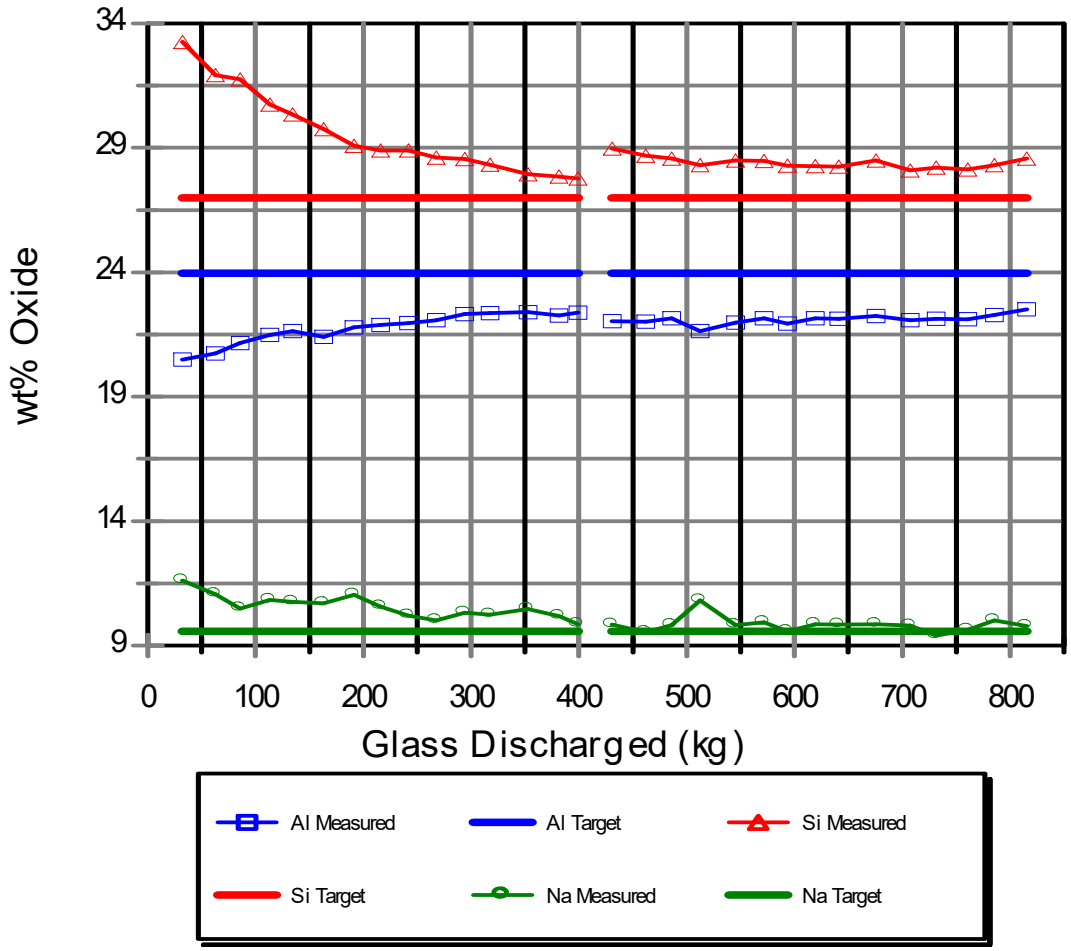

Figure 4.1.a. DM100 product and target glass compositions determined by XRF.

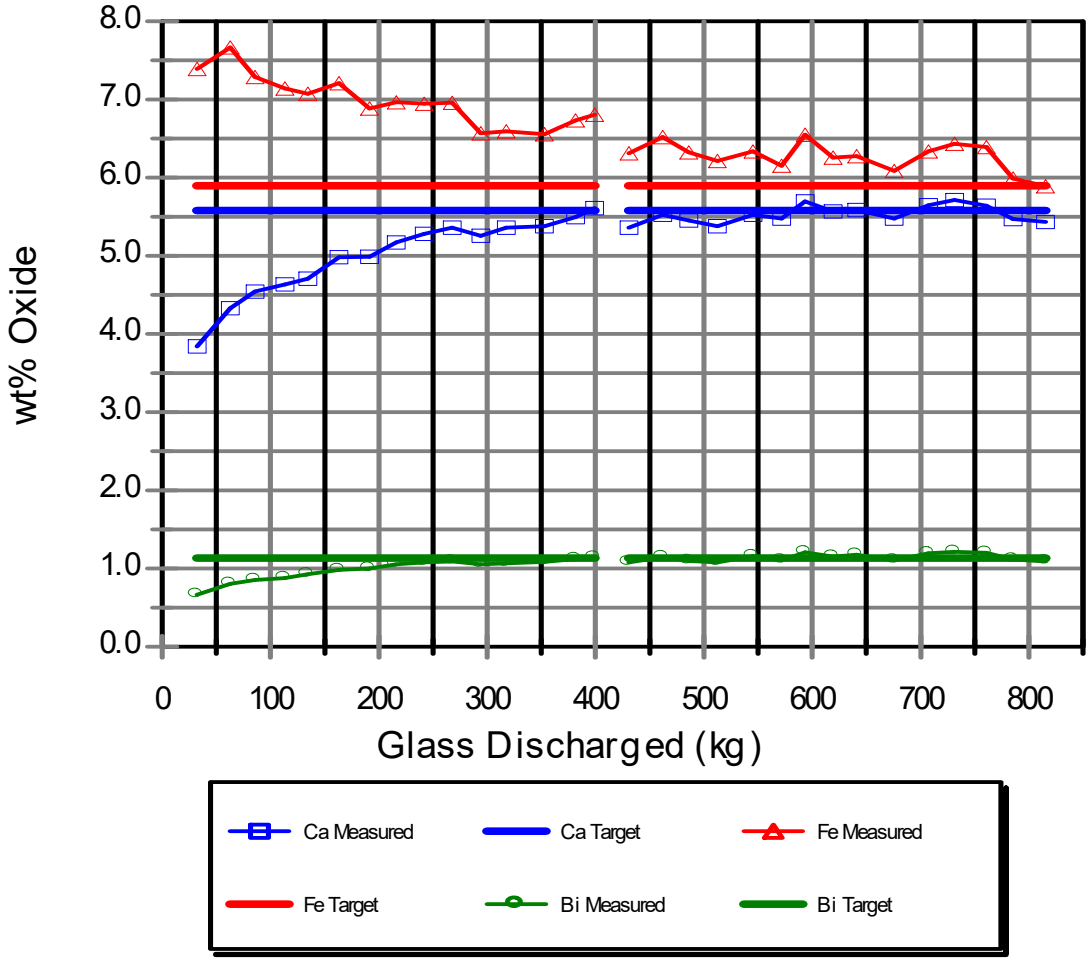

Figure 4.1.b. DM100 product and target glass compositions determined by XRF.

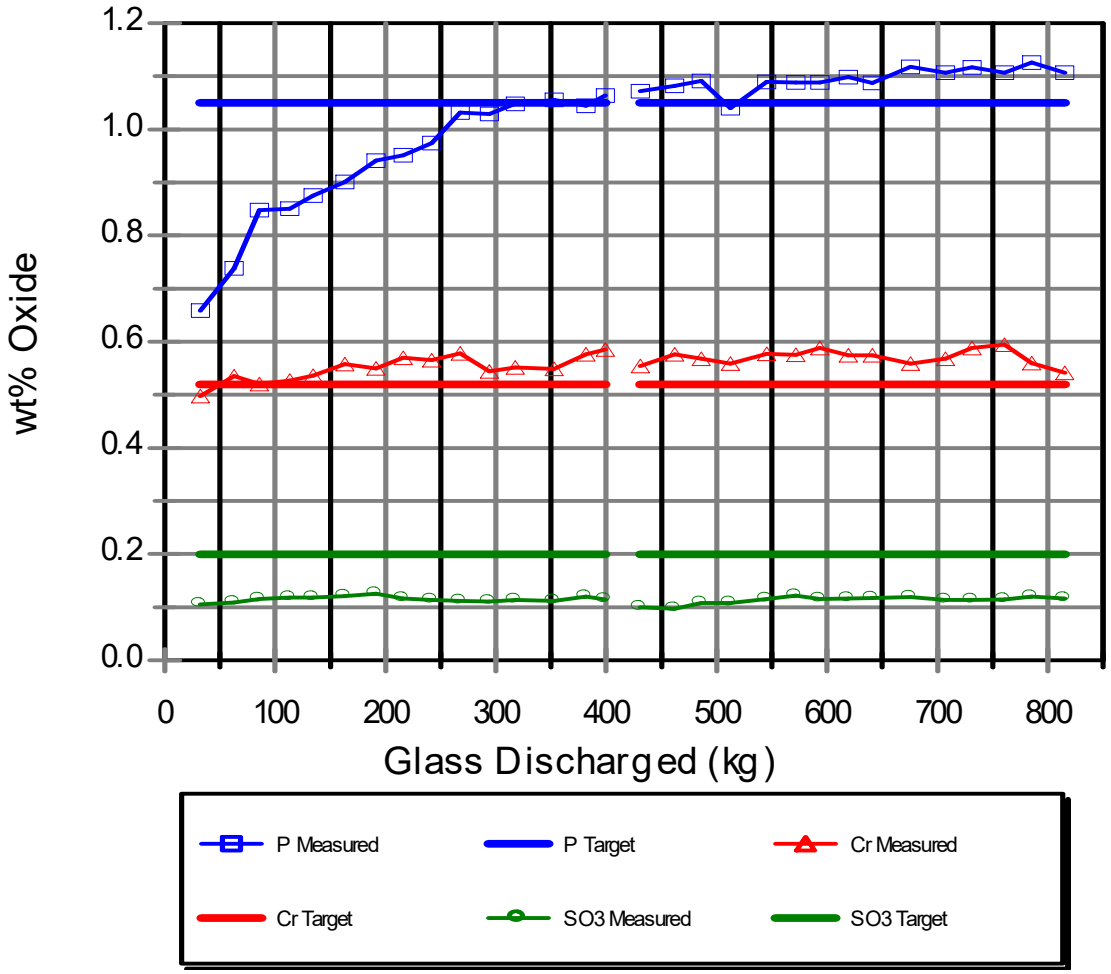

Figure 4.1.c. DM100 product and target glass compositions determined by XRF.

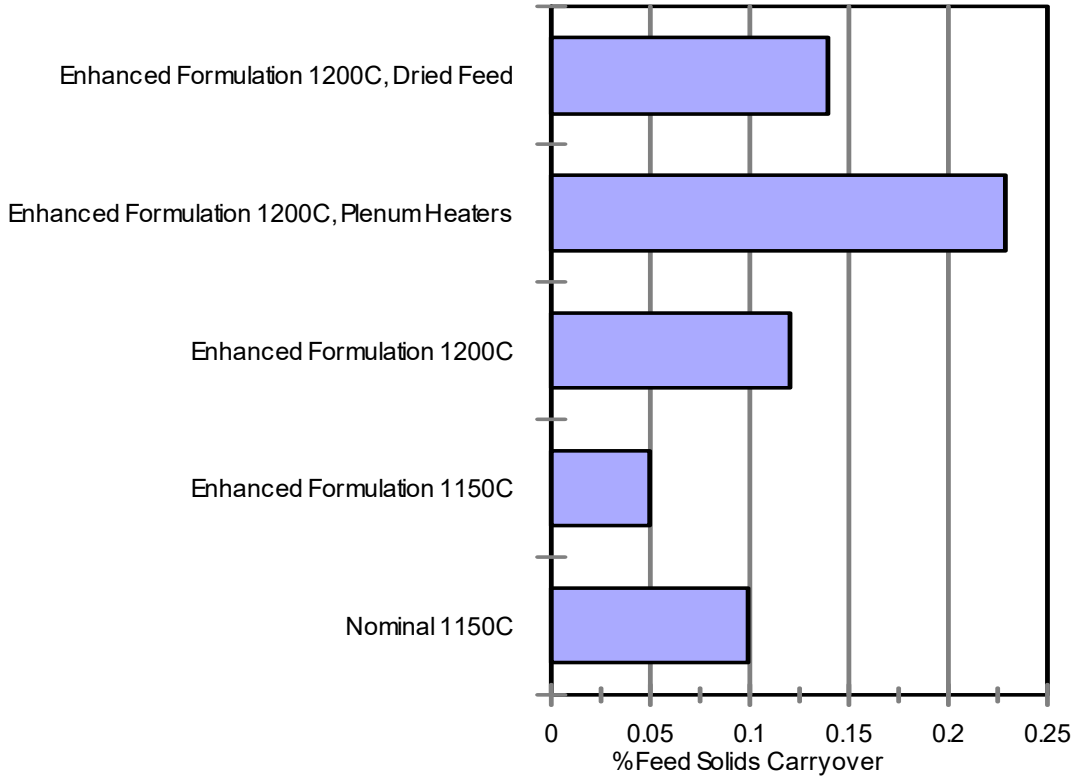

Figure 5.1. Percent feed solids carryover for tests with nominal formulation, enhanced formulation, plenum heaters, and dried feed.

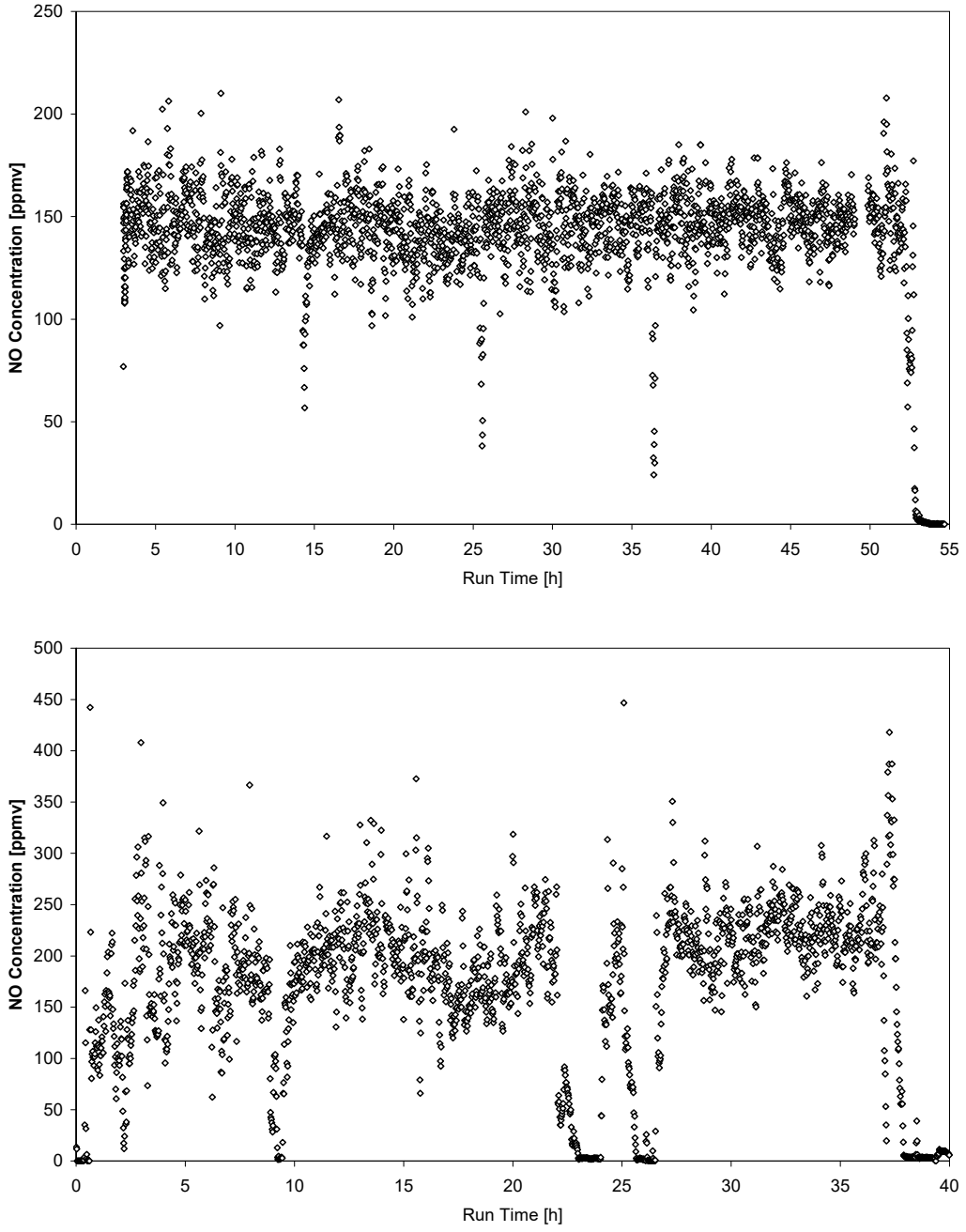

Figure 5.2. FTIR monitored NO emissions during tests with plenum heaters (top) and dried feed (bottom).

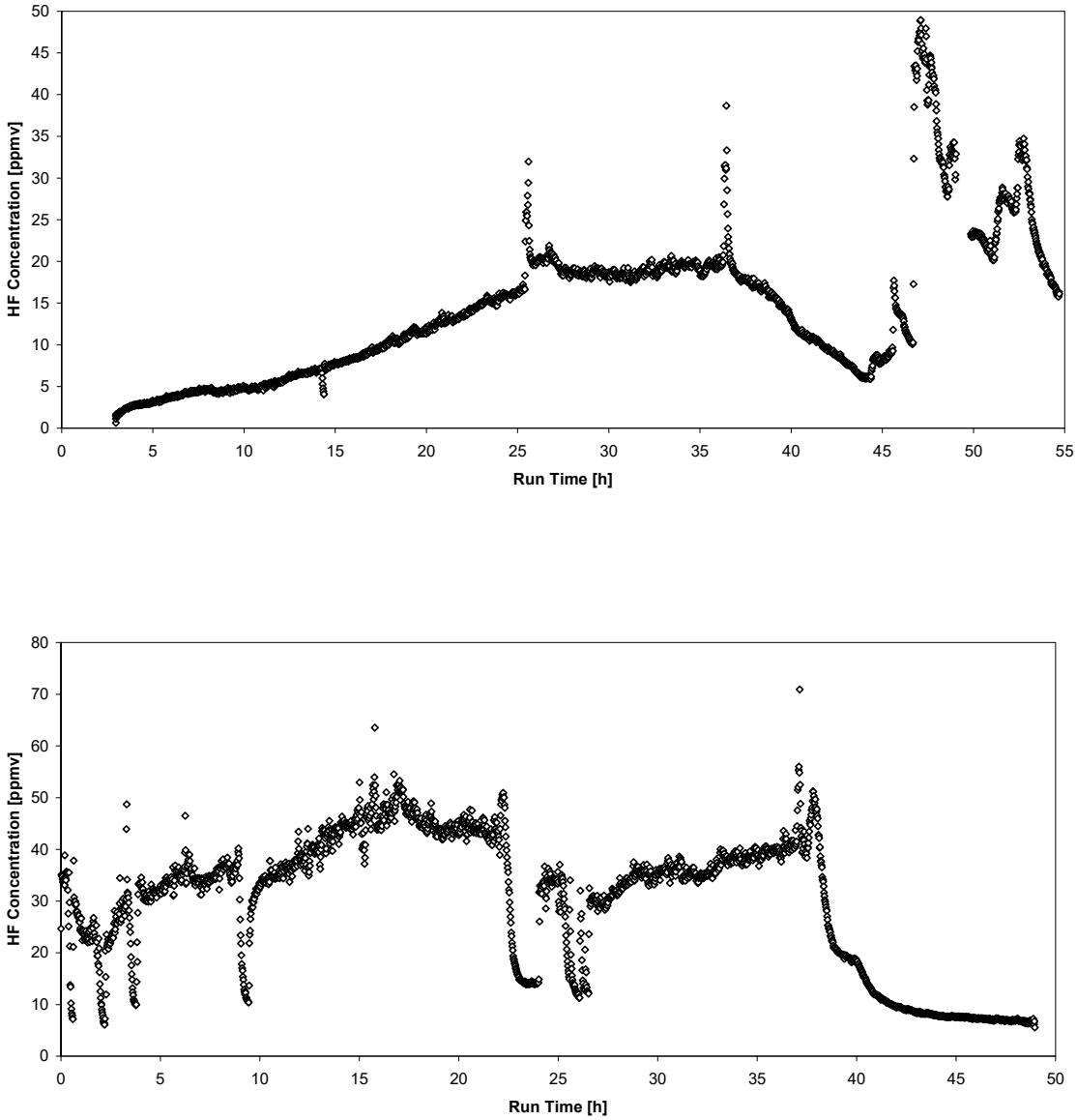

Figure 5.3. FTIR monitored HF emissions during tests with plenum heaters (top) and dried feed (bottom).

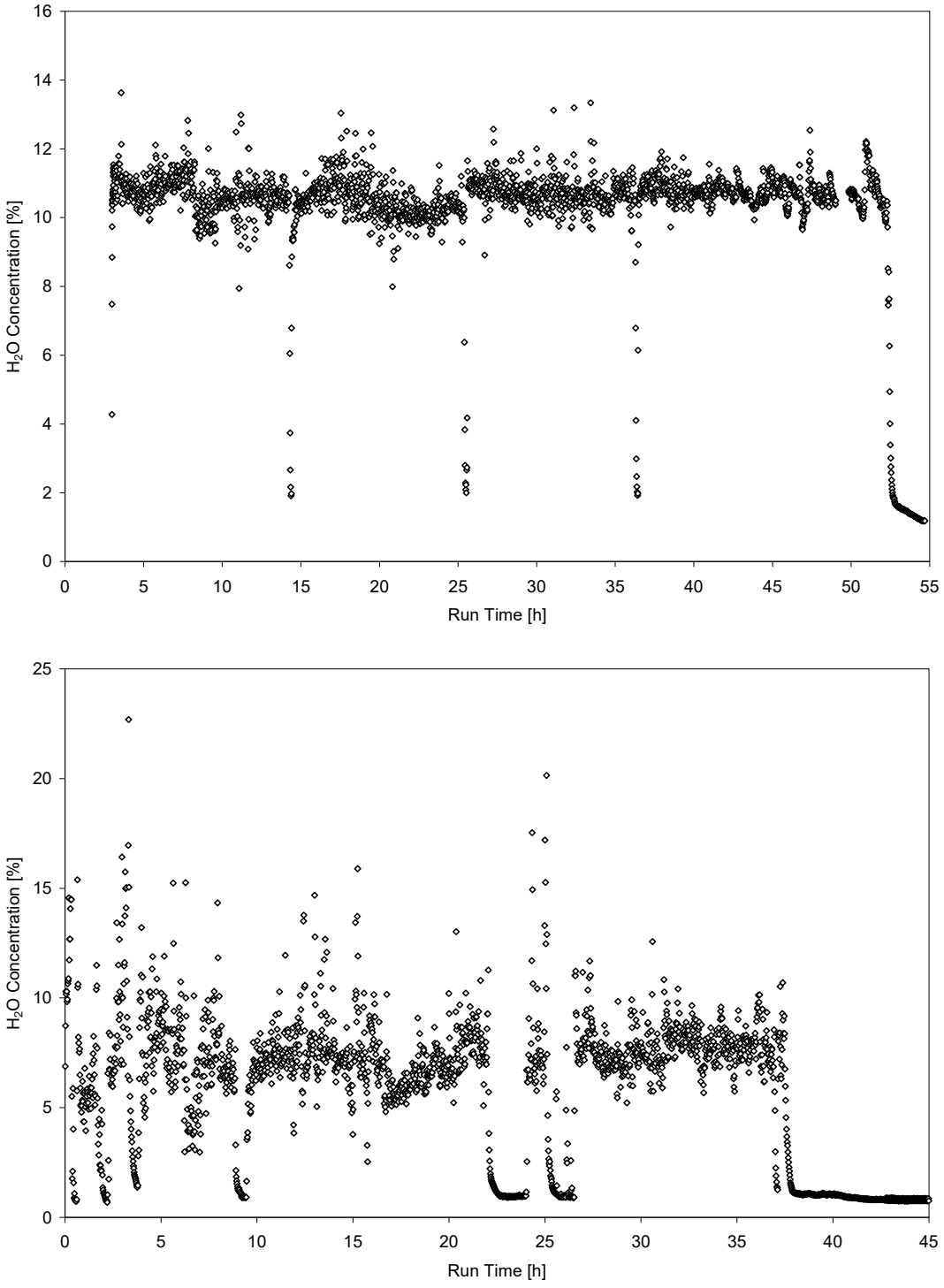

Figure 5.4. FTIR monitored water content of exhaust during tests with plenum heaters (top) and dried feed (bottom).