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Enhanced Sulfate Management in HLW Glass Formulations, VSL12R2540-1, Rev. 0

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

Office of River Protection

P.O. Box 450
Richland, Washington 99352

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Final Report

Enhanced Sulfate Management in HLW Glass Formulations

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Test Plan: Enhanced Sulfate Management in HLW Glass Formulations, VSL-12T2540-1, Rev. 0

This report describes the results of testing specified by the above Test Plan. The work was performed in compliance with the quality assurance requirements specified in the Test Plan. Results required by the Test Plan are reported. The test results and this report have been reviewed for correctness, technical adequacy, completeness, and accuracy.

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TABLE OF CONTENTS

List of Tables

List of Figures

List of Abbreviations

ACM	Aspen Custom Modeler
ANL-LRM	Argonne National Laboratory–Low-Activity Waste Reference Material
ASME	American Society of Mechanical Engineers
BDAT	Best Demonstrated Available Technology
BNI	Bechtel National, Inc.
CCC	Canister Centerline Cooling
CEM	Continuous Emissions Monitoring
DCP-AES	Direct Current Plasma – Atomic Emission Spectroscopy
DM	DuraMelter
DOE	Department of Energy
DWPF-EA	Defense Waste Processing Facility–Environmental Assessment
EPA	Environmental Protection Agency
FTIR	Fourier Transform Infrared Spectroscopy
HEPA	High-Efficiency Particulate Air Filter
HLW	High Level Waste
IC	Ion Chromatography
LAW	Low Activity Waste
NIST	National Institute of Standards and Technology
NQA	Nuclear Quality Assurance
ORP	Office of River Protection
PCT	Product Consistency Test
PNNL	Pacific Northwest National Laboratory
PVC	Polyvinyl Chloride
QARD	Quality Assurance Requirements and Description
RCRA	Resource Conservation and Recovery Act
SEM/EDS	Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy
SOP	Standard Operating Procedure
SRNL	Savannah River National Laboratory
TCLP	Toxicity Characteristic Leaching Procedure
TFCOUP	Tank Farm Contractor Operation and Utilization Plan
UTS	Universal Treatment Standard
VGF	Vertical Gradient Furnace
VSL	Vitreous State Laboratory
WTP	Waste Treatment and Immobilization Plant
XRF	X-ray Fluorescence Spectroscopy

SECTION 1.0
INTRODUCTION

The Low Activity Waste (LAW) tanks that are scheduled to provide the Hanford Tank Waste Treatment and Immobilization Plant (WTP) with waste feeds contain significant amounts of sulfate. The sulfate content in the LAW feeds is sufficiently high that a separate molten sulfate salt phase may form on top of the glass melt during the vitrification process unless suitable glass formulations are employed and sulfate levels are controlled. Since the formation of the salt phase is undesirable from many perspectives, mitigation approaches had to be developed. Considerable progress has been made and reported by the Vitreous State Laboratory (VSL) in enhancing sulfate incorporation into LAW glass melts and developing strategies to manage and mitigate the risks associated with high-sulfate feeds [1-6].

In contrast, little work has been performed on High Level Waste (HLW) glasses to investigate the behavior of sulfate during vitrification. HLW glass development for the WTP to-date has assumed low levels of sulfate in the glass (< 0.5 wt%). At such low levels, secondary sulfate salt formation is generally not a significant issue and, therefore, little effort was directed at improving sulfate loading in HLW glasses. However, pretreatment tests have indicated that sufficient interstitial liquid with high enough sulfate concentration can be carried over to HLW during the HLW/LAW separation process to increase sulfate content in HLW feeds to levels at which secondary sulfate phase formation may become an issue. In addition, the levels of insoluble sulfate compounds, which would be carried over with the HLW solids, are uncertain. Furthermore, Office of River Protection (ORP) System Plan projections frequently show a large fraction of the HLW batches being limited by sulfate. Preliminary tests on baseline WTP HLW glasses have shown that sulfate loadings need to be kept fairly low (about 0.5 wt% or less) to avoid sulfate phase formation. Formation of a secondary sulfate phase can result in many deleterious effects such as increased corrosion of metallic components, product quality issues, etc. The majority of the experience to-date in this area has been with sulfur in LAW since relatively little emphasis has been previously placed on sulfur in HLW. For LAW, sulfate layers on the glass surface increase the corrosion of metallic components such as bubblers, thermowells, level detectors, etc. [7-10]. A particular concern is accelerated corrosion of HLW bubblers because whereas the WTP LAW bubblers are designed to operate in glass melt environment that is more corrosive [7, 11], the effects of high sulfur HLW melts has not been considered in the design of the HLW bubblers [12]. Sulfate salt phases are easily leachable (much more so than glass) and they typically incorporate high concentrations of components such as Ba, Cr, Cs, Tc [8, 9, 11]. Therefore, the presence of sulfate salts in the HLW product could constitute a significant product quality issue. A substantial amount of work has been completed on Hanford LAW glasses to improve sulfate loading and it is anticipated that many of the same approaches can be used to improve sulfate loading in Hanford HLW glasses.

Based on early BNI WTP flow-sheet projections, the concentration of sulfate in the feed to the HLW vitrification facility were relatively low in most of the testing program to support the development of the present WTP HLW baseline. As a result, sulfate was not expected to be a significant component that would limit waste loading. Later process models suggested that sulfate concentrations in HLW glasses could likely exceed the highest concentrations tested in HLW crucible melts, and exceed values tested in scaled melter runs that showed segregated salt layers [13]. This is also reflected in more recent assessments, and particularly those performed for WTP system planning, which show that sulfate could indeed limit waste loadings in a significant fraction of the HLW feeds over the WTP mission. Based on the initial expectations, the concentrations of sulfate tested in both HLW crucible melts and melter tests were low such that the maximum sulfate concentration in HLW glasses formulated to support melter tests was only 0.13 wt% (as SO_3) [14]. Subsequently, melter tests were performed with an HLW glass formulated to support actual waste testing with a target SO_3 concentration of 0.19 wt% [15, 16], whereas HLW matrix glasses, designed to cover a much wider glass compositional region, contain a maximum of only 0.28 wt% of SO_3 [17].

In view of the very limited information on the likely range of sulfate solubilities in typical HLW glass melts, under the BNI WTP test program, twenty HLW glasses were selected to provide representative coverage of the expected compositional range of glasses to be produced at the WTP [18]. All of the selected glasses were previously formulated and characterized to support various tasks including melter testing, actual waste testing, property-composition model development, and support of HLW glass algorithm development. The solubility of sulfate in these glasses was measured by saturation with SO_3 by continuous gas bubbling. The measured sulfate solubilities (SO_3 in glass) ranged from 0.53 wt% to 1.60 wt%, with a median of 0.64 wt%. Two of these HLW glasses were processed on the DM10 melter system at VSL at successively higher sulfate concentrations until secondary phases were observed [19]. In one of these tests, the amount of sulfur contained in the glass upon the formation of secondary phases matched the amount determined in the bubbling experiments, while the other melter test produced a glass with about half the amount of sulfur as compared to the bubbling experiments. This difference indicates that sulfur solubility is not the only factor influencing the amount of sulfur that can be processed without the formation of deleterious secondary phases.

As part of the work performed at VSL for ORP, new glass formulations with waste streams containing variable amounts of sulfur were developed to extend composition spaces beyond those that have been previously investigated for the WTP [20]. The work was performed with four waste compositions specified by ORP [21]; these wastes contain high concentrations of bismuth, chromium, aluminum, and aluminum plus sodium. The tests were designed to identify glass formulations that maximize waste loading while meeting all processing and product quality requirements. The high-chromium waste was also high in sulfur, which in turn limited the waste loading to 32.5% with a sulfur concentration in the product glass of 0.45 wt% of SO_3 [20]. Subsequently, the glass composition for this waste stream was reformulated, allowing the waste loading to be increased to 45 wt% [22]. Glasses formulated for the high bismuth waste targeted 0.48 wt% of SO_3 at 50% waste loading and were processed on both the DM100 and DM1200 melter systems without the formation of any secondary sulfur phases [20, 23]. Taken together, these tests show the wide range in potential sulfur concentrations in projected HLW streams, the effect of the waste and glass composition on the formation of secondary sulfur phases, and the potential to mitigate the formation of secondary sulfur phases through manipulation of the glass formulation and glass forming additives.

The present report describes a series of small-scale crucible tests to determine sulfate solubility in HLW glasses, tests to assess the effect of compositional changes on sulfate solubility, and small-scale melter tests to determine maximum acceptable sulfate loadings in HLW feeds to the melter. The work was performed in accordance with the Test Plan for this work [24] and the ORP contract [25]. Glasses produced in previous melter tests using WTP and ORP waste and glass compositions were tested in the present work to determine sulfur solubility. In parallel, a glass formulation was developed for a previously untested HLW composition with one of the highest projected sulfate concentrations; that formulation was subsequently processed on the DM10 melter system at successively higher waste loadings to determine the maximum waste loading. Tests were also conducted on the DM10 on several HLW formulations which had been previously subjected to crucible-scale sulfur solubility testing; these formulations were selected based on sulfur solubility information for HLW glasses that was compiled in a previous report to WTP [18]; similar information for LAW glasses was compiled in a report to ORP [26].

1.1 Test Objectives

The principal objectives of the crucible scale and DM10 tests were to measure sulfur solubility and maximum feed sulfur concentrations that can be processed without the formation of secondary sulfate phases for a range of HLW glass compositions, as well as the sulfur solubility and maximum waste loading for a projected high sulfur HLW stream. High iron WTP glass compositions for HLW waste streams C-106/AY-102 [16, 27, 28], AZ-101 [22, 29] and AZ-102 [16, 30], as well as glasses formulated with waste streams containing high concentrations of bismuth, chromium, aluminum, and aluminum plus sodium [20, 31, 32] were identified for crucible scale and DM10 tests. A new projected high sulfur HLW composition was also identified for glass formulation development and subsequent DM10 tests.

Specific objectives of these tests were to:

- Determine the sulfur solubility in four glasses formulated with Hanford HLW high-iron streams and four glasses formulated with waste streams containing high concentrations of bismuth, chromium, aluminum, and aluminum plus sodium specified by ORP.

- Formulate a glass composition for a projected high sulfur HLW stream and investigate the maximum achievable waste loading.

- Determine the maximum amount of sulfur that can be processed on the DM10 without the formation of secondary phases for select glasses formulated with Hanford HLW high-iron streams and glasses formulated with waste streams containing high concentrations of bismuth, chromium, aluminum, and aluminum plus sodium specified by ORP.

- Determine the maximum waste loading that can be processed on the DM10 without the formation of secondary phases for a projected high sulfur HLW stream.

- Characterize the chemical composition of each glass discharged from the DM10 with particular emphasis on sulfur.

- Monitor off-gas constituents from the DM10 (N_2O, NO, NO_2, NH_3, CO_2, CO) by Fourier Transform Infrared Spectroscopy (FTIR).

To meet these objectives, the following tests were performed:

- Crucible-scale tests were performed to assess sulfur solubility using a batch saturation method as well as a gas bubbling method. In the latter method, glass melts were bubbled with gas mixtures that include sulfur to determine the solubility of sulfur in the glass using a procedure previously used with HLW and LAW glasses [18, 33];
- A new glass composition was formulated for a projected high sulfur HLW waste stream and characterized; and
- The highest sulfur feed concentrations and waste loadings that can be processed through the DM10 without the formation of secondary sulfate phases was determined for each of the tested glasses.

The DM10 melter system has been used for a range of tests with HLW glass compositions investigating production rate, increases in waste loading, volatile retention, and the tendency to form secondary phases [19, 20, 22, 29, 34]. For the present work, sufficient simulated HLW feed was procured to conduct a total of 200 hours of DM10 testing.

1.2 Quality Assurance

Testing was performed according to the existing quality assurance program that is in place at VSL. That 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, 2004; and DOE Order 414.1 C, Quality Assurance. The requirements of DOE/RW-0333P are applicable to the following specific aspects of this work:

- Crucible melt preparation of HLW glasses
- Analysis of HLW crucible melt glasses
- PCT of HLW glasses

The program is supplemented by a Quality Assurance Project Plan for ORP 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 Experimental Procedures

1.3.1 Crucible Melt Glass Batching and Preparation

HLW glasses are fabricated at the crucible scale using reagent grade chemicals in accordance with VSL SOPs [36]. The following briefly summarizes the procedural steps.

Glass preparation begins with a batching sheet that provides information on the required starting materials. The information includes the chemicals needed, identification of the chemicals according to the vendors and catalog numbers, the associated purity, together with the quantity required to produce a given amount of glass. The quantities of chemicals required are adjusted based on the reagent purities. Chemicals are weighed and batched according to the batching sheets.

After the starting materials are weighed and batched, a blender is used to mix and homogenize the starting materials before they are loaded into platinum alloy crucibles that are engraved with individual identification numbers. The loaded platinum/gold crucible is placed inside a Deltech DT-28 (or DT-29) furnace, the heating of which is controlled by a Eurotherm 2404 temperature controller. The melting temperature is 1150°C, at which the melt is kept for 2 hours. Mixing of the melt is accomplished mechanically using a platinum stirrer, beginning 20 minutes after the furnace temperature reaches 1150°C and continuing for the next 90 minutes. The molten glass is poured at the end of 120 minutes onto a graphite plate to cool before recovery.

1.3.2 Glass Analysis Procedures

1.3.2.1 Composition

With the exception of the lightest elements (i.e., boron and lithium), all glass components including SO_3 are measured by X-ray fluorescence spectroscopy (XRF). Test glasses are powdered to give -200 mesh samples before analysis with a PANalytical Axios mAX-Advanced wavelength dispersive XRF spectrometer. The XRF is calibrated over a range of glass compositions using standard reference materials traceable to National Institute of Standards and Technology (NIST) as well as other glasses, including the Argonne National Laboratory–Low-Activity Waste Reference Material (ANL-LRM), Defense Waste Processing Facility–Environmental Assessment (DWPF-EA) glass, West Valley Reference 6 glass, and WTP HLW and LAW glasses.

The analysis of sulfate salts is performed with direct current plasma – atomic emission spectroscopy (DCP-AES) and ion chromatography (IC). Samples of the sulfate phases removed from saturated glass samples are subjected to microwave assisted total acid dissolution in Teflon vessels according to VSL standard operating procedures. Twenty milliliters of a 1:5 mixture of concentrated $HF:HNO_3$ is diluted to 50 ml for use in dissolution. The sample solution is analyzed by DCP-AES. Sulfate in the solution is measured by IC (Dionex DX-120 and IonPac AS14) and reported as SO_3.

1.3.2.2 Viscosity

The viscosity of the glass melt, η, is measured using a Brookfield viscometer per VSL SOPs [36]. The viscosity is determined from the relation between torque and rotation speed of the spindle in the glass melt. Measurements are normally performed in the temperature range of 950°C to 1250°C and the data are interpolated to standard temperatures using the Vogel-Fulcher equation:

$$\ln \eta = [A/(T - T_o)] + C\ ,$$

where A, C, and T_o are fitting parameters. The equipment is calibrated at room temperature using standard oils of known viscosity and then checked from 950°C to 1250°C using a NIST standard reference glass (SRM 711). Both precision and accuracy of the viscosity measurement are estimated to be within ± 15 relative%.

1.3.2.3 Electrical Conductivity

The electrical conductivity, σ, is determined, according to VSL SOPs [36], by measuring the impedance of the glass melt as a function of frequency using a calibrated platinum/rhodium probe attached to a Hewlett-Packard model 4194A impedance analyzer. Measurements are performed over temperature ranges similar to those employed for the viscosity measurements (950°C to 1250°C). The resulting frequency dependent impedance data are analyzed in terms of an equivalent circuit to obtain the direct current conductivity. The measured data are then interpolated to standard temperatures using the Vogel-Fulcher equation:

$$\ln \sigma = [A/(T - T_o)] + C,$$

where A, C, and T_o are fitting parameters. Estimated uncertainties in the conductivity measurements are ± 20 relative%.

1.3.2.4 Product Consistency Test

The product consistency test (PCT; ASTM C 1285) is used to evaluate the relative chemical durability of glasses by measuring the concentrations of the chemical species released from 100-200 mesh crushed glass (75-149 μm) to the test solution (de-ionized water in this case). PCT tests on the HLW glasses are performed at 90°C, in accordance with the current WTP contract requirement. The ratio of the glass surface area to the solution volume for this test is about 2000 m^{-1} (typically, 10 g of 100-200 mesh glass is immersed in 100 ml deionized water). All tests are conducted in triplicate, in 304L stainless steel vessels, and in parallel with a standard glass included in each test set. The internal standard is the ANL-LRM reference glass [37] and/or the DWPF-EA glass, both of which have undergone round-robin testing. The leachates are sampled at predetermined times, the first of which is seven days. One milliliter of sampled leachate is mixed with 20 ml of 1M HNO_3 and the resulting solution is analyzed by DCP-AES; another 3 ml of sampled leachate is used for pH measurement.

1.3.2.5 Toxicity Characteristic Leaching Procedure (TCLP)

The TCLP is performed on glass samples per VSL SOPs [36] based on Environmental Protection Agency (EPA) SW-846 Method 1311. The test is used to determine the leach resistance of crushed glass (<3/8") in a sodium acetate buffer solution after 18 hours at 22°C with constant end-over-end agitation. A mass of 100 grams of glass is leached in 2 liters of TCLP extraction solution, according to the extraction method for non-volatiles. The surface area to volume ratio for this test is about 20 m^{-1}, which is about two orders of magnitude lower than that in the PCT. The leachate concentrations are measured by DCP-AES. The overall uncertainty associated with this test for glass samples is estimated from evaluation of VSL data to be ± 20%.

1.3.2.6 Determination of One-Percent Crystal Fraction Temperature ($T_{1\%}$)

One-percent crystal fraction temperature ($T_{1\%}$) is determined per VSL SOPs [36] as described below. Glass samples (about 5 grams each) are heat-treated in platinum, platinum-gold, or platinum-rhodium crucibles (5 ml) at a pre-melt temperature of 1200°C for 1 hour, followed by heat treatment for 70 hours at prescribed temperatures between 800°C and 950°C. At the end of the heat-treatment period, the glass samples are quenched by contacting the crucible with cold water. This quenching freezes in the phase assemblage in equilibrium with the melt at the heat-treatment temperature. The sample is then prepared for Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy (SEM/EDS) examination by grinding and sieving (−18 mesh). Microscopic and spectroscopic examination (Model JSM-5910LV, equipped with Oxford Instruments INCAEnergy 300 system) is used to determine the volume fraction of crystalline phases and the identity of the dominant crystalline phases. For each glass, heat treatments are performed to obtain non-zero vol% crystal data for at least three temperatures in order to reasonably constrain the $T_{1\%}$ value.

The $T_{1\%}$ value for each glass is obtained by linear regression of the heat-treatment temperature (°C) as the dependent variable versus crystal fraction (vol%) as the independent variable. The choice of vol% (which has the larger measurement error) as the independent variable, rather than the temperature (which has the smaller measurement error), is contrary to the selection that would normally be made for regression. However, as discussed in a previous $T_{1\%}$ modeling report [38], there are significant advantages to using this "inverse regression" approach in the present application. The differences in the $T_{1\%}$ values estimated using either choice of independent variable are small. Based on results from modeling studies, the standard deviation in estimating $T_{1\%}$ values is about 27°C [38].

1.4 Measurements of Sulfate Solubility in Glass Melts

1.4.1 Over-Saturation Melting

The sulfate solubility in selected glasses was measured using over-batching with sulfate. The selected HLW glasses were powdered to give –40 mesh (< 425 µm) samples. About 20 g of the glass powder was thoroughly mixed with reagent grade ammonium sulfate ($(NH_4)_2SO_4$). The amount of ammonium sulfate added was equivalent to 5 wt% of SO_3 in glass if all sulfur was retained in the glass. The glass/ammonium sulfate mixture was loaded into a Pt/Au crucible (50-ml) with cover and re-melted at 1150°C for 1 hour. At the end of 1 hour, the crucible was cooled naturally to room temperature and the glass recovered for examination. Washing of glass chunks to remove salt phases was followed by grinding (–200 mesh) and then washing of the glass powder to ensure removal of all sulfate salts. Analysis of SO_3 in the powdered and washed glass sample provided an estimate of sulfate solubility in the HLW glass.

The use of ammonium sulfate instead of other sulfate salts (e.g., Na_2SO_4) has the advantage of minimizing the effect on the original glass composition since its decomposition results in volatile ammonia. (Thermal decomposition of ammonium sulfate in the presence of zinc and other oxides has been developed as a means of recovering ammonia and sulfate [39]).

1.4.2 Gas Bubbling Experiments

The sulfate solubility (1150°C) in selected HLW glass melts was determined by analyzing the chemical composition of the glass melt in equilibrium with a molten sulfate phase at the designated test temperature. During the experiment, SO_3 is loaded into the glass melt gradually by bubbling a gaseous mixture of SO_2, O_2, and N_2 through the molten glass. The partial pressure of SO_3 (P_{SO_3}) is controlled through the chemical reaction between SO_2 and O_2 at the test temperature in the presence of a catalyst (the platinum bubbling tube). Gases are mixed, and the flow is regulated using a gas proportioner with the flow tubes calibrated for each individual gas stream. The mixed gas is then transported through flexible polyvinyl chloride (PVC) tubing fitted to a Pt bubbling tube, the other end of which is immersed in the molten glass. The flow rate of the mixed gas is 30 ml/min (at room temperature).

For each of the sulfate saturation experiments by gas bubbling, 100 grams of test glass is placed in a 200-ml Pt crucible and covered by a Pt sheet furnished with a slot for introducing the gas bubbling tube. The crucible is then loaded in the center of the platform of a Del-Tech furnace preheated to 1150°C. The gas mixture is introduced through the roof of the furnace, passing through preheated Pt tubes (24 to 36 inches in length). For each prescribed gas mixture of controlled P_{SO_3}, the test glass melt is bubbled continuously for 3.5 hours. At the end of each bubbling period, the setup is removed from the furnace for inspection for the development of a sulfate layer, and sampling (≈ 3-5 grams). A complete bubbling experiment usually involves multiple bubbling cycles, with step-wise increases of P_{SO_3}. Typically, two to three more bubbling cycles would be conducted after the onset of a sulfate layer in order to ensure saturation (see Section 3).

To determine sulfate solubility in silicate glass by means of bulk analysis (e.g., XRF), it is necessary to remove any separated sulfate salt from the glass in order to produce a homogeneous glass sample for analysis. Glasses sampled from gas-bubbled experiments, especially in the oversaturated condition, contain numerous inclusions of sulfate salt that are finely dispersed inside glass. Consequently, care must be exercised to separate the sulfate inclusions from the bulk glass. The glass samples collected at the end of each bubbling cycle are powdered (< 75 micron) and then washed to remove possible inclusions of segregated sulfate salt prior to analysis by XRF for chemical composition. The solvents used for washing include dilute (0.75 wt%) HNO_3 to remove alkali and calcium sulfates. Previous tests have shown that similar washing of homogeneous glass powder without sulfate inclusion does not remove significant amounts of any of the glass components.

1.5 DM10 Melter System Description

Testing was conducted on one of the two DM10 melter systems installed at the VSL, shown in Figure 1.1. A schematic diagram of the DM10 system is shown in Figure 1.2 and the principal components of the system are described in the following sections.

1.5.1 Feed System

The feed container is mounted on a load cell for weight monitoring and is stirred continuously except for periodic, momentary interruptions during which the weight is recorded. The material in the feed container is constantly recirculated, which provides additional mixing. 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. The feed rate is regulated by a peristaltic pump that is located between the recirculation loop and the feed tube.

1.5.2 Melter System

A DuraMelter 10 (DM10) system was used for this work. The Monofrax K3 ceramic refractory-lined melter includes two Inconel 690 plate electrodes that are used for joule-heating of the glass pool and a bubbler for mixing the melt. The DM10 melter has a melt surface area of 0.02 m^2 and glass inventory of about 8 kg. The glass product is removed from the melter by means of an air-lift discharge system.

1.5.3 Off-Gas System

For operational simplicity, the DM10 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, the exhaust gases passing through the transition line (between the melter and the first filtration device) can be sampled at constant temperature and air flow 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 HEPAs are held above 100°C 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.

1.5.4 Sampling Points

The sampling points available on the DM10 system and used in these tests are as follows:

- *Melter Feed*: Samples of the melter feed taken either from the parent feed batch or the melter feed line to provide confirmation of the feed composition.

- *Glass Product*: Samples of the glass product taken from glass that is air-lift discharged into steel cans.

- *Glass Pool*: Glass samples taken directly from the glass pool ("dip" samples).

- *Off-gas:* A sampling point located down stream of the HEPA filter was used for continuous emissions monitoring (CEM) by Fourier transform infra-red spectroscopy (FTIR) of a wide variety of gaseous species, including NO, NO_2, N_2O, CO, and SO_2.

SECTION 2.0
WASTE SIMULANT AND GLASS FORMULATIONS

2.1 WTP C-106/AY-102

This high-iron HLW simulant is based on actual waste samples from Hanford C-106/AY-102 waste blend and provided the compositional basis for previous tests on the DM100 [27] and DM1200 [16] melter systems. Analytical data for actual C-106/AY-102 waste samples were previously provided by the WTP Project for developing HLW glass formulations to support vitrification testing of actual C-106/AY-012 waste [13].

2.1.1 C-106/AY-102 Waste Simulant

Samples of Hanford C-106/AY-102 actual waste solids were shipped to Savannah River National Laboratory (SRNL) where they were combined and the composite sample analyzed. Washing and caustic leaching were the HLW pretreatments performed before analysis. Table 2.1 lists the analyzed composition of C-106/AY-102 in terms of non-volatile oxides, as provided by the WTP Project [40]. Table 2.1 also lists the cesium eluate from LAW pretreatment of AW-101 waste [41], which was blended with the C-106/AY-102 solids to give the HLW simulant in earlier tests [16, 27]. The blending of LAW pretreatment products is retained in the current HLW simulant so that test data to be obtained can be compared directly with the baseline data. The blending ratio was determined from the WTP dynamic process flowsheet model (G2), with the mass ratio of AW-101 waste oxides to C-106/AY-102 oxides equal to about 5.9×10^{-4}. The blended composition is given in Table 2.1. As can be seen, the AW-101 cesium ion-exchange eluate is essentially composed of a solution of sodium (nitrate) and boron, together with minor amounts of other alkalis and selected metal ions, including barium, cerium, copper, nickel, and tin. The blended waste composition is very similar to that of the C-106/AY-102 waste, primarily because of the low blending ratio. It should also be noted that the impact of blending on the iron concentration is negligible.

The blended waste in Table 2.1 contains 32 non-volatile components and was modified to give the HLW simulant for the previous and currents tests. The modifications are made to keep the number of components at a manageable level and they include: i) omitting the minor components (i.e., components that make up < 0.05 wt% in glass, which corresponds to about 0.12 wt% in waste, on an oxide basis); ii) omitting silver, which was not included in earlier C-106/AY-102 melter tests; and iii) substituting sodium for potassium, lanthanum for gadolinium, and zirconium for uranium (to eliminate the use of radioactive materials). Renormalization after these modifications results in the HLW waste simulant, the composition of which is shown in Table 2.1. It can be seen that iron is by far the most abundant component in the simulant (38.12 wt% Fe_2O_3), followed by aluminum and manganese (sodium and silicon are present in higher concentrations but both are part of the glass forming additives for the WTP).

To complete the formulation of the HLW waste simulant, the volatile components need to be defined. For this purpose, the concentrations of carbonate, nitrate, nitrite, and total organic carbon (TOC) from previous C-106/AY-102 melter tests are adopted [16, 27]. The complete HLW waste simulant is given in Table 2.2.

2.1.2 C-106/AY-102 Glass Formulations and Melter Feed Formulations

After definition of the composition of the blended C-106/AY-102 waste, new glass formulations were developed and tested at VSL to support actual waste testing [15]. The glass composition selected as the basis to vitrify C-106/AY-102 waste, HLW04-09, is presented in Table 2.2. The same glass formulation, with minor modifications including those made in defining the simulant described above, was used in previous melter tests [16, 27]. Another recently developed glass composition optimized to increase the glass production rate and waste loading [28] is also provided in Table 2.2.

The base glass HLW04-09 has a nominal waste loading of 37.10 wt%, incorporating 14.01 wt% of Fe_2O_3. This can be compared to the earlier HLW glasses formulated for high-iron wastes for the WTP Project, which are generally designed to demonstrate the capability to comply with the Contract Minimum Component Limits [42] and are limited to about 12.50 wt% of Fe_2O_3 [14]. Waste loadings in high-iron HLW glass formulations are found to be limited typically by the formation of spinel phases. Glass formulation efforts, however, have been successful in increasing the waste loadings (> 14 wt% Fe_2O_3) by suppressing spinel formation by increasing the alkali content, as described in an earlier report [15]. Subsequently the glass was reformulated as HLW-NG-Fe2 further increasing the waste loading to 42 wt%, incorporating 16.01 wt% of Fe_2O_3 [28].

2.2 WTP AZ-101

2.2.1 HLW AZ-101 Waste Simulant

Actual waste solids from tank AZ-101 were pretreated and analyzed at PNNL. The pretreatment started with washing of the solids (insoluble solids = 317.9 g) twice with 0.01 M NaOH solution (1000 g each), which was followed by caustic leaching with approximately 3 M NaOH at 85°C. After 8 hours of leaching, the slurry was then batch rinsed three times with 0.01 M NaOH (1200 g each). The resulting slurry, which had a solids content of 10.9 wt% with 130.2 g of total insoluble solids, was analyzed; the resulting chemical composition data are listed in Table 2.3. This composition [43] was the basis for the development of suitable glass composition for this waste for subsequent testing [44].

The AZ-101 simulant composition used for recent melter tests [22, 29] was also based on the actual waste analysis provided in Table 2.3. Uranium and most constituents at less than about half a weight percent oxide were omitted. Exceptions were chromium and sulfur, which were added to the waste simulant. Non-radioactive cesium was also added at the designated level of half a weight percent. The recipe for the resulting AZ-101 simulant is provided in Table 2.4. For the purpose of the 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 [30]. With the waste compositions defined, formulation of the HLW waste simulant proceeds in a straightforward fashion. In general, oxides and hydroxides are used as the starting materials, with slurry of iron (III) hydroxide (13% by weight) as the major constituent. Volatile inorganic components are added as the sodium salts, whereas organic carbon is added as oxalic acid.

2.2.2 Glass and Feed Formulation

Several glasses were developed and evaluated as candidates for the AZ-101 waste stream based on the actual waste sample analysis [44]. The glass deemed most suitable for the waste (HLW98-95) and variants used in previous melter tests [14, 22, 29] are provided in Table 2.5. The additive type and oxide percentage, 68.25%, are the same in these glasses. The small differences in the glass product compositions are the result of removal of uranium and several constituents at low concentrations, the exclusion of cesium and technetium pretreatment products, and renormalization of the waste oxide composition. The only difference between the glasses previously processed in the two melter tests is the exclusion of RuO_2 from the waste composition.

2.3 WTP AZ-102

The AZ-102 waste data, blending assumptions, and glass formulations used for these tests are essentially the same as those used in previous melter tests [16, 30] with only minor changes [45]. The composition of the HLW simulant was derived and specified in a corresponding BNI Test Specification [46].

2.3.1 AZ-102 Waste Simulant

Formulation of the AZ-102 waste simulant makes use of inventory data from the TFCOUP [47], calculated data from ACM modeling, and analytical data on Cs- and Tc-removal eluates from LAW pretreatment [48]. The composition of the AZ-102 Envelope D solids is based on the inventory data found in Revision 3A of the TFCOUP [47], as shown in Table 2.6. Revision 3A of the COUP provides information on minor components that were not included in earlier revisions [49] and the Best Basis Inventory (BBI) database (e.g., cadmium). The ACM model calculates the composition of the recycle stream (PWD01), which is then blended with the Envelope D solids based on the expected daily processing rates (i.e., 1.30E+04 lb/day for Envelope D solids and 1.28E+03 lb/day for the recycle stream on a dry solid basis). The resulting material is concentrated and pretreated through caustic leaching/water washing and ultra-filtration to produce the pretreated HLW solids. The separation factors due to caustic leaching and ultra-filtration are given in Table 2.6.

To complete the simulant formulation, the pretreated HLW solids must be blended with wastes from LAW pretreatment. In contrast to the blending scenario used in Part B1 tests, Sr/TRU removal products from pretreatment of Envelope C wastes were omitted from these tests per the Test Specification [46], although the then-current processing schedule suggested that some blending of Sr/TRU products from AN-102 (first Envelope C tank) may occur during the later stages of AZ-102 processing. Analytical data on eluates from Cs- and Tc-removal[1] on an Envelope B sample (AZ-102) [48] provide the compositional bases for the respective feed streams CNP12 and TEP12. The blending proportions are determined by the projected daily processing rate of sodium in the eluates (i.e., 1.71E+01 lb/day for Cs-removal and 3.32E-01 lb/day for Tc-removal). It can be seen in Table 2.6 that waste blending primarily leads to increases of sodium and nitrate in the HLW simulant.

The calculated composition of the blended HLW solids (HLP09b), which is shown in Table 2.6, lists a total of 55 components. A few of the components, however, have been left out of the blended solids in the Test Specification [46] because of unknown separation factors and low concentrations (e.g., Se and Y). In addition, similar to the approach taken during previous testing, radionuclides, noble metals (including silver) and minor components (< 0.02 wt% in glass on an oxide basis) are omitted from the simulant formulation. Another modification is the substitution of neodymium for praseodymium, another rare earth element, to reduce the number of components in the simulant. Cesium is spiked for analytical purposes, at an amount equivalent to 0.05 wt% in the glass product. The resulting HLW simulant formulation consists of 24 components, 20 of which are non-volatile.

As directed by WTP R&T [45], further modifications were made to the simulant composition. These included elimination of fluoride and chloride, but addition of extra carbonate to reach the target amount of 1.145 g per 100 g of waste oxide (as specified by the Test Specification [46]), in contrast with the previous AZ-102 melter tests, which employed simulants with a lower carbonate content. The final simulant composition is listed in Table 2.6.

2.3.2 AZ-102 Glass

With the elimination of Sr/TRU pretreatment products from the HLW simulant, new glass formulations had been developed and tested at VSL to support previous tests; the same glass composition was used for the present tests. The selected glass composition, HLW98-80, is presented in Table 2.7. On an oxide basis, this glass incorporates 23.76 wt% of Envelope D waste and 24.25 wt% of all wastes. These can be compared with the respective values of 26.29 wt% and 33.32 wt% for HLW98-66, the AZ-102 reference glass used in Part B1 [50]. The difference is primarily due to the increased limiting component of Fe_2O_3 in the new HLW simulant and the inclusion of Sr/TRU products in the old simulant. The iron content is increased to such an extent (51.80 wt% in the current simulant) that the reference glass HLW98-80 meets the contract specification by incorporating 12.53 wt% of Fe_2O_3, instead of the >21 wt% of (Al_2O_3+Fe_2O_3+ZrO_2) found in previous testing [50]. The reference glass HLW98-80 was the target glass composition used for previous DM1200 testing [16, 30].

Crucible melts of HLW98-80 have been prepared and tests performed to determine that it meets the necessary processing requirements. The measured viscosity and conductivity at

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[1] While it is recognized that technetium removal in pretreatment is no longer part of the WTP flow-sheet, this stream is retained in the present simulant in order to permit comparisons to previous test data.

1150°C are 51 P and 0.36 S/cm, respectively. Heat treatment of HLW98-80 at 950°C for over 70 hours results in < 0.1 vol% of spinel crystals. The target glass formulation for these tests, which is also given in Table 2.7, differs slightly from HLW98-80, with the removal of silver and the addition of small amounts of cesium. The additional constituents required to form the target test glass from the AZ-102 HLW simulant are boron, lithium, sodium, silicon, and zinc. The corresponding chemical additives that are the sources for these elements are selected based on previous testing and the WTP Project baseline glass forming chemicals.

2.4 ORP Defined Waste Streams

2.4.1 Waste Simulants

The waste stream compositions provided by ORP are given in Table 2.8 on an oxide basis [21] under the heading "Actual". Omission of radioactive components and renormalization of the simulated waste yields the compositions shown in Table 2.8 as "Non-Rad"; these compositions were used for the majority of previous crucible formulations and all of the HLW melter testing for ORP. However, once the final formulations were selected, additional crucible melts were performed using the appropriate radioactive components (i.e., thorium and uranium).

Actual HLW Hanford tank wastes are aqueous solutions with suspended solids and dissolved salts including hydroxides, nitrates, nitrites, halides, and carbonates. For the purpose of the 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 [30]. With the waste compositions defined, formulation of the HLW waste simulant proceeds in a straightforward fashion from the oxide compositions listed in Table 2.8. In general, oxides and hydroxides were used as the starting materials, including a slurry of iron (III) hydroxide (13% by weight). Volatile inorganic components were added as the sodium salts, whereas organic carbon was added as oxalic acid. The compositions of the resulting HLW waste simulants limited by bismuth, aluminum, and aluminum plus sodium used to produce glass for the current test are given in Tables 2.9 - 2.11.

2.4.2 Glass Formulation for Bi-Limited Waste

The composition and properties of the high-Bi glass previously produced in melter tests [20, 23] are given in Table 2.12. The glass formulation, HLW-E-Bi-6, meets all of the processing and product quality requirements imposed for these tests and has a waste oxide loading of 50 wt%. This exceeds both the minimum and maximum expected waste loadings provided in the scope of work [21] of 15 wt% and 40 wt%, respectively. The glass contains 6.7 wt% Bi_2O_3 and close to 5 wt% P_2O_5. The Bi_2O_3 content is more than three times the WTP contract minimum for Bi_2O_3 (2 wt%). The PCT leach rates are over an order of magnitude lower than those of the DWPF-EA glass and the TCLP leachate concentrations are all below the WTP Delisting Limits. The measured processing parameters are within acceptable ranges. As noted above, the viscosity is towards the high end of the acceptable range. The risk of foaming during cooling of the poured glass in the canister was addressed in previous work [23].

2.4.3 Glass Formulation for Al-Limited Waste

Two 45 wt% waste loading glasses were developed for the high aluminum HLW waste stream, HLW-E-Al-27 and HWI-Al-19, and were among those processed on both the DM100 and DM1200 [20, 31]. The compositions and the characterization results of the two glasses are given in Tables 2.13 and 2.14. The glass formulations meet all of the processing and product quality requirements imposed for these tests and have a waste oxide loading of 45 wt%. This exceeds both the minimum waste loading of 25 wt% and approaches the maximum expected waste loading of 50 wt% provided in the Scope of Work [21]. The glasses contain 23.97 wt% Al_2O_3, which is more than two times the WTP contract minimum for Al_2O_3 (11 wt %). The principal difference between the two glasses is the approximate four weight percent increase in boron oxide concentration at the expense of silica in HWI-Al-19. All of the measured processing parameters are within acceptable ranges. The PCT leach rates are over an order of magnitude lower than those of the DWPF-EA glass and the TCLP leachate concentrations are all below the WTP delisting limits. Sodium aluminosilicate formation (e.g., nepheline) on heat treatment (especially canister centerline cooling (CCC) heat treatment) is a known concern with high-aluminum formulations and was the waste-loading-limiting factor for these glasses. The glasses produced little crystallization (~1.9 vol%) after CCC heat treatment.

2.4.4 Glass Formulation for Al-Na-Limited Waste

A 47 wt% waste loading glass was developed for the high aluminum and sodium HLW waste stream, HLW-E-ANa-22, and was processed on the DM100 [20]. Table 2.15 presents the composition of the glass tested on the DM100 and the measured properties of the crucible glass. The glass formulation, HLW-E-ANa-22, meets all of the processing and product quality requirements imposed for these tests and has a waste oxide loading of 47 wt%. This is more than twice the minimum waste loading of 20 wt% and approaches the maximum expected waste loading of 60 wt% provided in the Scope of Work [21]. The glass contains 21.34 wt% Al_2O_3, which is nearly twice the WTP contract minimum for Al_2O_3 (11 wt%). The measured processing parameters are within acceptable ranges. The PCT leach rates are more than a factor of four lower than those of the DWPF-EA glass and the TCLP leachate concentrations are all below the WTP delisting limits. Sodium aluminosilicate formation (e.g., nepheline) on heat treatment (especially canister centerline cooling heat treatment) is a known concern with high-aluminum formulations and was the waste-loading-limiting factor for this glass formulation. The glass produced very little crystallization (~0.5 vol%) after CCC heat treatment and the heat treated glass also meets the PCT requirements by a wide margin.

2.5 High Sulfur HLW Waste Stream

2.5.1 Simulant Composition

The composition of the high sulfur HLW simulant for testing was selected from waste batches for which waste loadings in glass formulation development are limited by the WTP SO_3 constraint [42]. Per the River Protection Project System Plan 6 [51], there are over 800 such waste batches at WTP, with the SO_3 concentrations ranging from 1.04 wt% to 4.38 wt%. If the minimum component limit in HLW glass for SO_3 of 0.5 wt% is used [42], the waste loadings in HLW glass products for these wastes range from a high of 48 wt% down to a low of 11 wt%. The selected waste batch is Number 4028 in System Plan 6 [51]. This waste has a SO_3 concentration of 4.15 wt%. This waste contains over 50 component oxides, including radioactive oxides such as UO_3. In order to maintain a manageable number of components and to eliminate the use of radioactive materials for melter testing, all minor components (i.e., < 0.1 wt%) and radioactive oxides were omitted in the definition of the HLW simulant. The resulting HLW composition, which is given in Table 2.16, contains 96.83 wt% of the original oxides. The HLW simulant composition was obtained by normalization of the oxide composition, which is also given in Table 2.16.

The HLW simulant listed in Table 2.16 shows considerable compositional differences (in wt% oxide) from other HLW simulants used in earlier melter tests. Most of the previously investigated HLW simulants are high in Fe_2O_3 and/or Al_2O_3. By contrast, the predominant component in the current HLW simulant is Na_2O (36.12 wt%), which is known to play a significant role in determining sulfate solubility [4, 5, 18, 26, 33]. There are also relatively high concentrations of P_2O_5 (10.99 wt%) and Al_2O_3 (10.83 wt%) in the simulant, followed by Bi_2O_3 (6.98 wt%) and Fe_2O_3 (6.55 wt%). Table 2.17 provides a recipe to produce the HLW simulant for 100 kg of waste oxides. The compositions of volatile components in the HLW are not given in the System Plan; therefore the concentrations used in previous melter testing are substituted in deriving the recipe in Table 2.17. The volatiles and their respective concentrations are: carbonate (4.65 g/100 g oxide), nitrate (0.784 g/100 g oxide), nitrite (0.012 g/100 g oxide), and organic carbon (0.026 g/100 g oxide).

2.5.2 Glass Formulation

New HLW glass formulations were developed and tested for the high-sulfur waste in Table 2.16 at the highest possible waste loading while maintaining acceptable durability and processing characteristics. Sulfate solubility and crystal formation were expected to be the primary waste loading limiting constraints. Previous experience and data from development of Hanford LAW glasses with high sulfate loadings were used to guide the present HLW glass development work. These include use of high concentrations of CaO and Li_2O and addition of V_2O_5 to the glass composition. Where available and applicable, glass property-composition models were used to assist in the design of new HLW glass formulations for testing. Models for viscosity, electrical conductivity and 1% crystal fraction temperature ($T_{1\%}$) were frequently used to guide glass formulation design, whereas PCT models were rarely used because PCT is normally not a constraining property for HLW glasses.

Table 2.18 lists the waste loadings and glass forming additives for each of the twenty HLW glass formulations (HLWS-01 through -20) that were developed and tested. Table 2.18 also provides the target compositions of these glasses. It is seen in Table 2.18 that the waste loadings for the HLWS series of glasses ranged from 26.50 wt% to 34.00 wt%, which corresponded to target SO_3 concentrations of 1.22 wt% to 1.56 wt% in glass, respectively for the simulant composition used in the preparation of crucible melts. These SO_3 concentrations are high when compared to the sulfate solubilities measured for a group of HLW glasses in a previous study [18]. That study included 20 HLW glasses selected from various sources (e.g., glasses formulated to support melter tests and glasses designed statistically to support property-composition model development). The results of the study showed that sulfate solubilities for HLW glasses are similar in magnitude to those found for LAW glasses, with a range of 0.53 wt% to 1.12 wt% and an average of 0.70 wt% after exclusion of an outlier of 1.60 wt% [18]. As stated above, the HLW simulant for glass composition development is relatively high in Na_2O (36.12 wt%). Consequently, although Na_2O is commonly used as an additive in HLW glass formulations, it was not used in formulating the HLWS glasses (Table 2.18). By contrast, both CaO and V_2O_5 are seldom used in HLW glass formulations but are added in this case in an effort to increase SO_3 loadings.

Crucible melts were prepared for the HLWS series of glasses and the compositions of the resulting glasses were analyzed by XRF. Table 2.19 presents the compositional data. It is seen that the measured SO_3 contents are in general lower than the targets defined by the waste loadings. This is likely due to the volatilization of sulfur during glass melting. The solubilities of sulfate in the HLW glasses were measured by over-saturation melting and, in some selected cases, gas bubbling (Section 1.4). In addition to sulfate solubility, all prepared glasses were characterized with respect to crystal formation after heat treatment at various temperatures; viscosity, electrical conductivity, and PCT responses were also measured for selected glasses. Table 2.20 summarizes the characterization data for the HLWS glasses. Table 2.20 also includes viscosity and electrical conductivity values calculated at selected temperatures from Vogel-Fulcher equations fitted to the experimental data.

The sulfate solubilities measured for the initial members of the HLWS series (HLWS-01 through -08) are either beneath or only slightly above the SO_3 concentrations required by the waste loadings being tested. Figure 2.1 graphically compares the measured sulfate solubilities of the HLWS glasses with the target SO_3 values as defined by the waste loadings. Recall that sulfate solubility needs to be distinguished from the amount of sulfate allowed in the melter feed to avoid sulfate salt formation, which is typically lower. The former is a thermodynamic property while the latter also involves important kinetic effects and other effects stemming from the complex environment during actual melter processing. In order to identify a candidate glass formulation suitable for melter testing, the thermodynamic sulfate solubility should be high enough to provide for a margin above the target sulfate level in glass. The amounts of CaO and/or V_2O_5 are increased in the formulations of HLWS-09 through -11. This generally increases the sulfate loading with limited deleterious effects on other glass properties. For example, replacing 2 wt% of SiO_2 in HLWS-07 with CaO in HLWS-10 significantly increases the sulfate solubility (from 1.10 wt% to 1.55 wt%, by over-saturation melting), while the viscosity and electrical conductivity of HLWS-10 are acceptable for processing. (Replacing 2 wt% of SiO_2 in HLWS-07 with V_2O_5 in HLWS-11, however, resulted in very little change in sulfate solubility). Of the 20 glasses tested, HLWS-09 has the highest measured sulfate solubility; it also has the highest CaO concentration in glass at 8 wt% (2 wt% V_2O_5). Further increase in CaO in these glass formulations, however, is limited by the formation of apatite (see below).

Figure 2.2 relates the measured sulfate solubility with the contents of selected oxides (and sum of alkalis oxides) including Li_2O, Na_2O, B_2O_3, CaO, and V_2O_5. No simple correlation is obvious in Figure 2.2, with the possible exception of CaO, which suggests a general relation of increasing sulfate solubility with increasing CaO concentration. As was found in an earlier study

[18], simple relationships between sulfate solubility and glass composition are not easily discernible in these complex multi-component systems.

Sulfur solubilities (as wt% SO_3) in HLWS series glasses from batch saturation and gas bubbling experiments are given in Table 2.20 and illustrated in Figure 2.3. The solubilities measured by batch saturation are on average about 14% less than those measured by gas bubbling, even though in three cases the same or higher solubility values were obtained by the batch saturation method. Earlier sulfur solubility measurements on LAW glasses [33] also showed similar behavior with the solubilities measured by batch saturation being on average about 14% less than the values measured by gas bubbling.

The principal crystalline phases that formed upon heat treatment of the HLWS glasses are spinel and calcium phosphate (apatite). In a few cases, a water-soluble phase also resulted but it could not be identified after sample processing for SEM examination; their presence was inferred from the voids found in the sample. Based on previous experience, this could be due to lithium phosphate. The measured crystallinity data were used to estimate the $T_{1\%}$ values and the regression results are given in Table 2.21. The estimated $T_{1\%}$ values range from 734.14°C to 1053.56°C, which can be compared with the processing requirement of 950°C. A preliminary study on HLW glass formulations for bismuth phosphate wastes showed that it is challenging to develop compliant glasses for wastes with high concentrations of CaO and P_2O_5 [52], the primary limiting factor being the heavy crystallization of calcium phosphate upon heat treatment. In addition to sulfate, the target waste composition in Table 2.16 is also relatively high in P_2O_5. Addition of CaO to increase sulfate solubility in HLW glass formulations for this waste therefore needs to be balanced with minimizing the formation of calcium phosphate.

The melter processing rate of formulation HLWS-09 was assessed by crucible scale experiments in a Vertical Gradient Furnace (VGF). Details of the VGF test method have been reported earlier [31]. In the VGF, a dried feed sample is subjected to a temperature gradient from 600°C to 1150°C over time periods of 30 to 60 minutes and the degree of feed conversion over the test duration is evaluated. The images of the reacted feed sample after 30 and 60 minutes VGF tests are shown in Figure 2.4. Overall, the feed samples showed very porous structures probably due to extensive degassing. The degree of conversion from feed to glass melt was relatively low in comparison to fast melting melter feed samples investigated before [23, 31, 32]. Based solely on the extent of feed conversion, the melt rate of this feed would be assessed a one (slow melting) on a scale of one to five described in an earlier report [31]. However, compared to other slow melting HLW feed samples (e.g., slow melting high-Al HLW feeds) that visually appeared unmelted and crusty, the HLWS-09 VGF sample had a glossy appearance indicating a greater level of melting.

The glass formulation HLWS-09 was selected for melter testing (see Section 4.0). This glass was characterized with respect to TCLP. Testing was performed on a glass prepared without sulfate but otherwise identical to HLWS-09 in target composition (HLWS-09A). The TCLP release of Cr is 0.04 ppm, which can be compared with the Universal Treatment Standard (UTS) limit of 0.60 ppm (not applicable because of the EPA BDAT (best demonstrated available technology) for HLW) and the delisting limit of 4.95 ppm. The TCLP release of Ni from HLWS-09A is 0.44 ppm (UTS limit of 11 ppm and delisting limit of 22.6 ppm).

SECTION 3.0
GAS BUBBLING EXPERIMENTS

A series of eight HLW glasses were subjected to a gas bubbling procedure to determine the sulfur solubility over a wide compositional range. The procedure described in Section 1.4.2 is one of two crucible scale methods used to determine sulfur solubility in glasses at VSL. The sample test matrix and experimental results are provided in Table 3.1. Sulfur solubility measurements were made on glasses produced from melter tests; the analyzed compositions of these glasses are provided in Table 3.2. The sulfur solubility ranged over nearly a factor of two, from about 0.66 wt% SO_3 for several glasses formulated for high iron wastes to 1.25 wt% SO_3 for a glass formulated for high aluminum waste. The results also show that through glass formulation, the sulfur solubility can be increased for a given waste stream; the sulfur solubility was increased from 0.65 to 0.83 wt% SO_3 for the C-106/AY-102 actual waste simulant and from 1.09 to 1.25 wt% SO_3 for the high aluminum waste simulants.

Small inclusions of secondary sulfate phase were observed in glass samples subjected to solubility measurements by both batch saturation and gas bubbling. These inclusions were uniformly distributed in the samples and were evident visually. These inclusions were not analyzed during the present work. However, similar inclusions observed during earlier sulfur solubility tests on HLW glasses [18] were analyzed for their composition. The inclusions were dissolved by washing with dilute acid (HNO_3), NaCl solution and de-ionized water and the resulting solutions were analyzed by DCP-AES and IC. The inclusions were alkali (Li, Na, K) sulfates rich in Cr, P and alkaline earth components depending on the specific glass composition. SEM/EDS analysis identified a sulfate nodule with high concentrations of Na, Li and Sr in a glass sample with high Sr concentration [18].

A comparison of measured sulfur solubility for HLW glasses from the current and previous work [18] was conducted to discern compositional trends in the glass associated with sulfur solubility. Thirty nine glasses, eight shown in Table 3.2, eleven from the development of the HLWS-09 glass formulation (see Section 2.5.2; glass samples were measured for sulfur solubility using two methods, only those obtained by the bubbling procedure are evaluated here), and twenty from previous tests [18] were evaluated. The composition and measured sulfur solubility for glasses from the previous work are provided in Table 3.3. As observed in the development of the HLWS glass compositions and the earlier study [18], simple relationships between sulfate solubility and glass composition are not easily discernible in multi-component systems. Depictions of sulfur solubility and various oxide concentrations are shown in Figures 3.1 – 3.7. No clear trends are observed for sulfur solubility for most elements, particularly sodium and total alkali. Only a limited number of glasses were formulated with vanadium and all those are for the ORP defined high sulfur waste (see Section 2.5.1); however, all formulations with two weight percent vanadium oxide have sulfur solubilities of greater than 1.2 wt% SO_3. Sulfur solubility does appear to increase with increasing calcium content, with the outliers containing high concentrations of strontium. Sulfur solubility does appear to increase with increasing calcium and strontium content, with the outliers containing low concentrations of boron. Sulfur solubility is also shown to increase as the combined concentrations of calcium, strontium, and boron increases with no obvious outliers from the broad trend.

These results are generally consistent with results from Hanford LAW glass testing previously conducted at the VSL, except that Li_2O was found to be highly beneficial in improving sulfate solubility in LAW glasses. For a large number of Hanford LAW streams, sulfur is the main component that limits waste loading in glass. Therefore, improving the incorporation of sulfur into glasses was a major focus of the Hanford LAW glass development work. In support of this effort, a large number of Hanford LAW glasses spanning a range of alkali and sulfur concentrations were prepared and characterized for sulfate solubility. Sulfate solubilities were measured by the batch saturation method, and by the gas bubbling method. Glass former additives were varied in an effort to find the optimum set of additives to improve sulfate loading in glass while meeting all processing and product quality requirements. Approximately 156 LAW glasses were prepared and measured for sulfate solubility by the batch saturation method under the WTP program for BNI, Inc. In a separate effort in support of ORP to develop higher waste loading LAW glasses, sulfate solubilities of about 168 glasses were measured by the batch saturation method and another 19 glasses were measured by the gas bubbling method.

The LAW glass former additives that were varied include Al_2O_3, B_2O_3, CaO, Fe_2O_3, Li_2O and SiO_2. Oxides of vanadium and phosphorous also were tested as potential additives to improve sulfate loading in LAW glasses. Initial results showed that addition of oxides of Ca, Li, V and P improve sulfate loading in LAW glasses [5, 53-56]. Beneficial effect of addition of alkaline earth oxides to soda-lime-silicates to improve sulfate solubility has been reported previously [57]. Based on the results from the WTP work, in the higher waste loading LAW glass development effort for ORP, higher concentrations of oxides of Li, Ca and V were tested [26, 33, 58-62]. Li_2O additions were made only in those glasses that were not limited in waste loading by the waste alkali concentration. The results showed that oxides of Li, Ca, and V are beneficial in improving sulfate solubility in LAW glasses, with addition of Li_2O and CaO being most effective in lower alkali, higher sulfate compositions.

SECTION 4.0
MELTER OPERATIONS

Melter tests were conducted with three different HLW waste simulants and associated glass formulations at various feed sulfur concentrations on the DM10 between 3/26/12 and 7/12/12. These tests produced over 360 kg of glass from over a metric ton of feed. Feeds processed, sulfur concentrations, production rates, and measured melter parameters for the tests are summarized in Table 4.1. The tests were nominally 20 hours in duration and were distinguished by differences in feed composition as follows:

- Test 1: High aluminum HLW waste with HWI-Al-19 glass formulation
    - 1A: Target SO_3 Conc. 0.4 wt%
    - 1B: Target SO_3 Conc. 0.6 wt%
    - 1C: Target SO_3 Conc. 0.8 wt%
    - 1D: Target SO_3 Conc. 1.0 wt%
    - 1E: Target SO_3 Conc. 1.3 wt%
    - 1F: Target SO_3 Conc. 1.6 wt%
    - 1G: Target SO_3 Conc. 1.4 wt%
    - 1H: Target SO_3 Conc. 1.3 wt%

- Test 2: High iron C-106/AY-102 HLW waste with HLW-NG-Fe2 glass formulation
    - 2A: Target SO_3 Conc. 0.7 wt%
    - 2B: Target SO_3 Conc. 0.6 wt%
    - 2C: Target SO_3 Conc. 0.5 wt%
    - 2D: Target SO_3 Conc. 0.4 wt%

- Test 3: High sulfur and bismuth HLW waste with HLWS-09 glass formulation
    - 3A: Target SO_3 Conc. 1.20 wt%, 28 wt% waste loading
    - 3B: Target SO_3 Conc. 1.42 wt%, 33 wt% waste loading
    - 3C: Target SO_3 Conc. 1.63 wt%, 38 wt% waste loading
    - 3A-2: Target SO_3 Conc. 1.20 wt%, 28 wt% waste loading
    - 3D: Target SO_3 Conc. 1.71 wt%, 28 wt% waste loading
    - 3E: Target SO_3 Conc. 1.91 wt%, 28 wt% waste loading

The sulfur content of the feed was adjusted by the addition of concentrated sulfuric acid to the nominal feeds for all except Tests 3B and 3C. Waste loading was increased in Tests 3B and 3C to increase the sulfur content, which also had the effect of increasing the concentration of all other waste components as well as the feed water content. Tests 1E, 2D, and 3A-2 were conducted over shorter than nominal duration, either to use the amount of available feed or time to collect additional data, lower the sulfur content at the end of Test 2, or return the composition of the melt pool to the nominal waste loading composition after Test 3C.

Attempts were made to replicate the melter configuration and operating conditions used for previous melter tests with HLW simulants [16, 19, 20, 22, 23, 27-32, 34]. These conditions include a near complete cold cap, which is between 80-95% melt surface coverage for the DM10 since a 100% cold cap tends to lead to "bridging" in smaller melters. The bubbling rate was adjusted to approximate a feed rate of 3 kg/hr (glass production rate of 1300 kg/m^2/day) and provide the desired complete cold cap (90-100% of melt surface covered with feed). Power was supplied to the electrodes to target a glass temperature of 1150°C throughout the tests. This approach permitted the direct comparison of results between current and previous tests with respect to the onset of secondary phase formation. The glass pool was sampled a minimum of three times in separate locations at the end of each segment to detect the presence of secondary phases. If secondary phases were detected, the melt pool was bubbled and sometimes fed water, then sampled again to verify the removal of the secondary phase prior to a following test segment or melter shut down. In between Tests 1 and 2, 31 kg of glass that had been discharged from the DM100 while processing the HLW-NG-Fe2 formulation [28] was fed through the DM10 melter to change the glass pool composition from the high aluminum glass to the high iron glass.

Throughout the tests, the feed was easily processed without clogs and resulting disruptions to the feed. An interruption of approximately one day occurred during Test 3A due to loss of water supply to the building. A smaller interruption of about an hour and a half occurred during Test 3E due to a clog in the riser, which complicated the discharge of glass. The cold cap was observed through a view port on top of the melter over the duration of the tests. No significant foaming was visible during the tests. Changes in bubbling rate were made in each test in response to observations of the cold cap in order to maintain the desired feed rate.

4.1 Melter Operations Data

The test average feed rates ranged between 2.7 and 3.3 kg/hr, yielding production rates between 1250 and 1440 kg/m^2/day for all but Test 3A-2 in which feed was processed at a faster rate. Glass temperatures (2 and 4 inches from the melt pool floor) averaged within 10°C of the target glass temperatures throughout most of the tests, with Tests 3B, 3C, and 3A-2 being the exceptions. Lower glass temperatures occurred during these tests as a result of changes in the glass composition as the waste loading was increased, creating a much less resistive glass and the need for higher current, which exceeded tolerances for the electrodes. The glass temperature 4 inches from the melt floor averaged 4 to 21°C less than the temperature measured 2 inches from the melt floor and varied more with the level of glass in the melter and changes in the cold cap than did the temperatures measured lower in the melt pool. Electrode temperatures were 150 to 200°C lower than the temperature of the glass pool during tests with the high aluminum and iron glasses. This differential was lower by about a factor of two in tests while processing the

HLWS-09 glass formulation; the electrodes were hotter in these tests due to the lower resistance of the glass pool.

The discharge temperature was maintained above 1000°C throughout most of the tests to prevent the freezing of glass in the chamber during discharge. Plenum temperature measurements were typically between 520 and 600°C in the thermowell and about 10 to 60°C cooler at the exposed thermocouple once the cold cap was established. This difference is similar to recent tests processing HLW feeds on the same melter, suggesting that the thermocouple placement results in the exposed thermocouple being partially shielded and the thermowell being closer to the bubbling outlet. The exposed plenum thermocouple read 100 to 150°C lower than the thermocouple in the thermowell during tests 3A-3C suggesting that the exposed thermocouple was partially coated with feed. The gas temperature at the film cooler averaged between 256-303°C, which results from the combined effects of the plenum temperature, the amount of added film cooler air, and the temperature of the added film cooler air. Test average glass pool resistance ranged between 0.18 and 0.22 ohms for tests processing the high aluminum and iron formulations but only between 0.12 and 0.17 ohms while processing the HLWS-09 glass formulation. The lowest resistance was associated with the changes in glass composition associated with the higher waste loading tests. Test average bubbling rates ranged from 0.4 – 1.2 lpm while processing the high aluminum feed, 1.2 – 2.6 lpm while processing the high iron feed, and 0.4 – 2.2 lpm while processing the HLWS-09 glass formulation, indicating that the high iron feed is the most difficult to process and the high aluminum is the easiest. HLWS-09 did not show any processing issues even though the crucible-scale VGF test had indicated a relatively slow feed conversion rate. However, the HWI-Al-19 formulation did not show a higher glass processing rate than the HLW-NG-Fe2 formulation when processed on the DM100 at constant bubbling rate [28, 32], which suggest that the DM10 bubbling rate is not always a good predictor of relative processing rates observed on larger melters. A vacuum of about 1 inch of water was maintained on the melter throughout the tests. Power supplied to the electrodes ranged between 5 and 6 kW throughout the testing consistent with the relatively constant feed rate and feed water content used throughout the tests.

4.2 Secondary Phase Formation

The primary objective of these melter tests was to determine the maximum amount of sulfur that could be processed in the feed and retained in the glass product without forming secondary phases for three different HLW and glass formulations. The results summarized in Table 4.1 and displayed in Figures 4.1 – 4.3 are described here for each waste composition as follows:

Test 1 - HWI-Al-19: The sulfur content of the feed was adjusted for each test segment by the addition of sulfuric acid to the feed. The feed concentration of sulfur was increased progressively over five test segments from 0.4 to 0.6, 0.8, 1.0 and 1.3 wt% SO_3 on a glass basis without any observations of secondary sulfur phases. Over this testing period the concentration of sulfur in the glass increased to 0.8 wt% SO_3. Testing was resumed targeting a sulfur content of 1.6 wt% SO_3 at the end of which secondary phases were observed on several samples from the glass pool indicating the presence of a separated sulfate layer on the melt pool surface. After removing the sulfate layer, testing was continued with 1.4 and 1.3 wt% SO_3 on a glass basis in the feed. Secondary phase was observed on numerous glass pool samples after processing 1.4 wt% SO_3 and minor amounts after processing 1.3 wt% SO_3. After the melt pool recovered the sulfur lost during idling between Tests 1E and 1F, the sulfur concentration in the glass fluctuated mainly between 0.8 and 1.0 wt% SO_3. The lack of secondary phase during the initial test and the limited amount of secondary phase observed in the second test indicate that the limiting feed sulfur concentration is about 1.3 wt% SO_3. The associated level of sulfur in the glass is about 0.8 wt% SO_3 which is significantly less than the 1.25 wt% SO_3 saturation level measured in the bubbling tests (see Section 3.0).

Test 2 - HLW-NG-Fe2: The sulfur content of the feed was adjusted for each test segment by the addition of sulfuric acid to the feed. The feed concentration of sulfur was decreased progressively over four test segments from 0.7 to 0.6, 0.5 and 0.4 wt% SO_3 on a glass basis with numerous observations of secondary sulfur phases at the two highest sulfur concentrations. No secondary phase was observed on glass samples after processing feed containing 0.5 wt% SO_3 and a very limited amount was observed after processing feed containing 0.4 wt% SO_3. After the first test segment, sulfur levels in the glass fluctuated between 0.3 and 0.4 wt% SO_3. The results indicate that the limiting feed sulfur concentration is about 0.5 wt% SO_3 with the associated level of sulfur in the glass of 0.35 wt% SO_3, which is significantly less than the 0.83 wt% SO_3 saturation level measured in the bubbling tests (see Section 3.0).

Test 3 - HLWS-09: The sulfur content of the feed was adjusted for the first four test segments by increasing the proportion of sulfur-containing waste to the additives. The feed concentration of sulfur was increased progressively from 1.20 wt% SO_3 at 28% waste loading, 1.42 wt% SO_3 at 33% waste loading, 1.63 wt% SO_3 at 38% waste loading, and back to 1.20 wt% SO_3 at 28% waste loading to return the glass to the nominal composition. No secondary phases were detected in any of these tests. Over this testing period, the concentration of sulfur in the glass increased to 1.2 wt% SO_3. Testing was resumed by adjusting the sulfur content of the feed by the addition of sulfuric acid to the feed. The feed concentration of sulfur was increased progressively over two additional test segments to 1.71 and 1.91 wt% SO_3 on a glass basis without any observations of secondary sulfur phases. Over the last two test segments the concentration of sulfur in the glass increased to 1.6 wt% SO_3. The lack of secondary phases observed in these tests indicates that the limiting feed sulfur concentration is greater than 1.91 wt% SO_3 and the associated level of sulfur in the glass is greater than 1.6 wt% SO_3, which is consistent with the 1.78 wt% SO_3 saturation level measured in the bubbling tests (see Section 3.0). The composition is also shown to be robust with respect to the formation of secondary phases resulting from changes in glass composition resulting from changes in waste loading. The very high sulfur tolerance of this formulation, which rivals that of the best LAW formulations, is noteworthy, particularly in comparison to the present WTP limit for HLW glass of 0.5 wt% SO_3.

During DM10 melter tests, the SO_3 content in the HLWS-09 glass reached a value close to the equilibrium sulfate solubility limit measured at crucible scale without forming a secondary sulfate phase, while such secondary phase formed at SO_3 contents much lower than the equilibrium solubility values for the other two HLW compositions. Similar observations have been noted while comparing crucible and melter test results with high sulfur LAW feeds. While processing melter feeds with very high sulfate concentrations, a molten sulfate salt phase forms in the cold-cap region during processing. This phase may exist as transient droplets or be sufficiently extensive to produce a separate salt phase that becomes mechanically disengaged from the rest of the cold cap. Once formed, the salt phase is slow to dissolve into the underlying glass melt; consequently, the salt phase typically forms before the underlying glass melt is saturated with sulfate [1, 3, 4, 26, 54, 62]. If the feed rate is sufficiently low (which is clearly undesirable), the equilibrium sulfate saturation concentration in the glass can be approached more closely before a separate salt phase forms. However, in general, as the feed rate is increased, for the same sulfate concentration in the feed, the salt phase appears progressively earlier. Thus, in practice, the formation of a sulfate phase is governed by both thermodynamic and kinetic factors and, therefore, the effects of both must be considered in order to avoid the formation of such phases during operations. While the equilibrium sulfate solubility limit can be measured, the factors that control the kinetics of sulfur incorporation into the glass melt are not well understood. Some glass compositions are able to reach sulfate concentrations close to the equilibrium solubility limits before secondary sulfate phases form, whereas such phases form at much lower concentrations in other compositions.

SECTION 5.0
MELTER FEED, GLASS AND EXHAUST ANALYSIS

5.1 Analysis of Melter Feed

Melter feed used for the melter tests for the HWI-Al-19 and HLW-NG-Fe2 compositions was produced by NOAH Technologies Corporation for testing on the DM1200 [63] and DM100 [28]. The as-received feeds were analyzed to determine the additions required to achieve the target solids content of 500 g glass per liter feed and to confirm the chemical composition. The ORP defined high sulfur waste was produced at VSL from reagent grade chemicals. The feed for the HLWS-09 formulation was produced by the addition of kyanite, boric acid, calcium carbonate, vanadium pentoxide, silica, and zircon to the simulant in the calculated proportions for each test. Feed from the end of two test segments from each composition was sampled and analyzed to determine physical properties and confirm the chemical composition.

Measured properties and analyzed chemical compositions of the feed samples compared to the targets are given in Tables 5.1 – 5.4. The measured feed solids contents were mostly somewhat above the calculated target value; however, all of the feeds that were processed were within ten percent of the target values. The as-received HWI-Al-19 feed was diluted to achieve the desired feed solids content. Measured feed properties for the two samples from each feed type are very similar showing the consistency of feed over each feed type. Differences in the two HLWS-09 samples are due to the intentional changes in waste loading, which result in different water contents and feed solids content. The XRF and DCP analyses confirm the composition of the as-received feed except for boron and sodium in the feed for the HLW-NG-Fe2 formulation. Based on these results, borax was added to the feed to correct the boron and sodium deficiencies. Results from analysis of melter feed produced by NOAH that was sampled from the melter feed tank generally show good agreement with the target composition for the major components. Of the oxides with a target concentration of one percent or greater, only the XRF values for phosphorus in the HWI-Al-19 feed and manganese and zirconium had deviations of greater than 10% from target. The absolute deviations were less than 0.2 wt% for phosphorus and zirconium and less than 0.75 wt% for manganese; these differences are not expected to affect the objectives of the present tests.

For the HLWS-09 samples, all oxides targeted at greater than four weight percent were well within ten percent of the target composition, while some of the oxides with target concentrations between one and four percent deviated by greater than ten percent in some of the samples. In the first sample, oxides of bismuth, iron, nickel, and phosphorus were between eleven and sixteen percent above target; however, the absolute deviations are less than 0.4 wt% and are therefore not expected to affect the objectives of the present tests. In the second sample taken from composited residual feed, manganese and zirconium were from sixty to eighty percent below target concentrations. Much of this deficit can be attributed to sampling and settling out of heavy minerals, particularly zircon, and is not indicative of the feed that was processed. Analysis of the discharged glass (see Section 5.2) shows highly variable concentrations of both elements varying twenty percent above and below their respective target concentrations during Tests 3B and 3C from which the feed was sampled.

Boron and lithium concentrations measured by DCP were within six and four percent of their respective target values for the melter feed for all three compositions, validating the use of the target values for normalizing the XRF data. Several oxides targeted at low concentrations in at least one the three glass formulations, including Ba, Ca, Cd, Mg, Ti, and Zn, were observed in the feed sample analysis due presumably to trace level contamination. Similarly, chlorine, manganese, strontium, titanium, and zinc were measured at low concentrations (0.01 to 0.09 wt%) in feed samples despite not being included in the target composition. Potassium was measured at a third of weight percent in glass produced from feed for the HLW-NG-Fe2 formulation, similar to previous observations in tests on the DM100 with the same feed batch. Sulfur concentrations are below target in feed samples due to volatilization during crucible melting, as expected.

5.2 Discharge Glasses

Over three hundred and sixty kilograms of glass was produced in these tests. The glass was discharged from the melter periodically using an airlift system and collected in custom fabricated square carbon steel cans. The discharged product glass was inspected for secondary phases, sampled by removing sufficient glass from the top of each can for total inorganic analysis. No macroscopic secondary phases were observed on any of the discharge glasses. Listings of product glass masses, sample names, and discharge dates are provided in Tables 5.5 – 5.7. The glass discharged from the turnover with 31 kg of glass from DM100 testing [28] is not included.

Discharge glass samples were crushed and analyzed directly by XRF. The target values for boron and lithium oxides, which are not determined by XRF, and DCP analyzed concentration of select glasses were used to calculate boron and lithium concentrations and for normalizing the XRF data to 100 wt%. The XRF analyzed compositions of all discharged glass samples are provided in Tables 5.8 - 5.10. The majority of the XRF analysis results compared favorably to their corresponding target values and also corroborated much of the feed sample analysis (see Section 5.1.). Of the oxides with a target concentration of one percent or greater, the average XRF values from tests processing the HWI-Al-19 formulation were all within 10% of the target values. For the tests processing the HLW-NG-Fe2 formulation, the average analyzed glass composition had deviations greater than 10% for aluminum, manganese, and zirconium. The deviations from target are attributable to the composition of the melt pool at the start of testing varying from the target composition (despite the 31 kg of glass turnover prior to testing with the HLW-NG-Fe2 formulation) and the deviations noted in feed samples (see Section 5.1). The composition of glasses discharged while processing the HLWS-09 formulation are more difficult to compare to the target compositions due the changing glass pool composition from the intended changes in waste loading and variability in zircon and manganese feed to the melter. Deviations from target concentrations were similar to those observed from feed sample analysis in that constituents targeted between one and four percent such as iron, manganese, zirconium, and nickel deviated from target by 10 to 25% for some test segments. The effect was exaggerated in Test 3A and 3D due to the differences in the initial glass pool composition and the target, as also observed for the additives calcium and vanadium in the initial test. Minor constituents such as barium, chlorine, potassium, magnesium, titanium, and zinc were over represented in the glass product at about the same frequency and magnitude as in the feed samples (see Section 5.1). Oxides of arsenic, cadmium, copper, neodymium, antimony, strontium, and zinc were present in the melt pool at the onset of Test 3 as a result of conducting another test sequence [64] in between the test series with the HLW-NG-Fe2 and HLWS-09 formulations.

The discharge glass compositions over the course of testing are illustrated in Figures 5.1 - 5.11. Most oxides approximate their respective target or analyzed feed values and varied little during testing after three melt pool turnovers had been completed for each composition. At the beginning of testing, the major oxides of Al, B, and Bi increase in concentration at the expense of Mg, Si, Zn, and Zr as the glass pool transitions to the HWI-Al-19 formulation. Subsequently, while processing the HLW-NG-Fe2 formulation, the major oxides of Fe, Mn, and Si increase in concentration at the expense of Al, B, and Ca. Major oxides such as those of aluminum, bismuth, calcium, silicon, sodium, and iron reach steady state concentrations after the first test segment of the first two test series and vary little over the remainder of the tests. Exceptions are aluminum and calcium in the latter portion of Test 1. At the onset of testing with the HLWS-09 formulation, the major oxides of Ca, P, V, and Bi increase in concentration at the expense of Fe, Si, Zr, and toxic metals as the glass pool transitions from the C-106/AY-102 composition processed prior to Test 3 [64]. The glass composition continues to change as the waste loading is increased: bismuth, iron, phosphorous and sodium, increase in concentration at the expense of calcium, silicon, and vanadium. This trend was reversed in the latter portion of Test 3 upon return to nominal waste loading and adjustment of the feed sulfur concentration. The manganese and zirconium concentrations in tests processing the HLWS-09 formulation were highly variable due presumably to some settling out of minerals in the feed.

5.3 Glass Pool Samples

The glass pool samples were obtained by dipping a rod into the glass melt at the end of each test to detect any secondary phases on the glass pool surface, verify the composition of the glass pool, and to determine the melt level to quantify the amount of glass in the melt pool. A list of all dip samples including sample names, sampling dates, glass pool depth, and secondary phase observations are given in Tables 5.11 - 5.13. A minimum of three dip samples at three locations in the melt pool were taken to fully characterize the melt pool surface for secondary phases. Samples were also taken prior to each test and after bubbling periods for removing secondary phases to verify the lack of secondary phases on the melt surface prior to testing. There was visual evidence of secondary phases in dip samples taken during the latter portion of testing while processing the HWI-Al-19 formulation, after most tests while processing the HLW-NG-Fe2 formulation, and not with any samples while processing the HLWS-09 formulation. Pictorial examples of secondary phases from tests with the HWI-Al-19 and HLW-NG-Fe2 formulations are given in Figures 5.12 and 5.13, respectively. The significance of the secondary phase observations with respect to sulfur concentrations and solubility is detailed in Section 4.2. The analysis of the glass pool samples corroborates the composition of the discharge glasses, as shown in Tables 5.14 – 5.16. Comparison of the analyzed compositions of dip samples taken prior to and after each test with each glass formulation further demonstrates the changes in composition of the melt pool during each test series.

There was sufficient recoverable secondary phase from dip samples taken after Test segment 2B for XRF analysis, the results of which are presented in Table 5.17. The secondary phase consists primarily of sodium sulfate, as expected, with less than one weight percent each of many of the feed components. Also of note is the greater than one weight percent of potassium oxide in the secondary phase despite the lack of potassium in the target composition and only a third of a percent measured in glass produced from feed samples. Although not measured in the secondary phase or present in the melter feed from the present tests, cesium and technetium have been observed to concentrate in similar secondary phases during tests with LAW wastes [65].

5.4 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 HEPA filter to prevent analyte loss due to condensation prior to monitoring. A summary of average and concentration ranges monitored during each test is provided in Tables 5.18 - 5.20. The analytes listed are those that were thought likely to be observed during the test based on previous work; no other species were detected in the off-gas stream by FTIR. Monitored emissions were a function of the nitrogen oxide, organic carbon, and water content in the feed and the feed rate. The feed content of nitrogen oxides and organic carbon is very low in these three waste streams and therefore the monitored emissions of nitrogen oxides and byproducts of incomplete combustion are uniformly very low or are below detectable levels. The percent moisture in the exhaust averaged between 1.7 and 3.2. The most abundant nitrogen species monitored was NO, which is consistent with previous tests in which nitrates and nitrites were present in the feed.

SECTION 6.0
SUMMARY AND CONCLUSION

Tests were conducted at the crucible scale and on the DM10 melter to measure sulfur solubility and maximum feed sulfur concentrations that can processed without the formation of secondary sulfate phases for a range of HLW glass compositions, as well as the sulfur solubility and maximum waste loading for a projected high sulfur HLW stream. High iron WTP glass compositions for HLW streams from C-106/AY-102 [16, 27, 28], AZ-101 [22, 29] and AZ-102 [16, 30], as well as glasses formulated with waste streams containing high concentrations of bismuth, chromium, aluminum, and aluminum plus sodium [20, 31, 32] were tested at either the crucible scale or in the DM10 melter. Sulfur solubility in HLW glasses was addressed by two different methods at crucible scale (over-batching and gas bubbling) and by processing of HLW feeds at various sulfur contents on the DM10 melter system.

A glass composition was formulated (HLWS-09) for a projected high sulfur HLW stream with a nominal waste loading of 28 wt% and a target sulfur concentration of 1.20 wt% SO_3. A variety of additive blends were tested to identify a glass with the highest sulfur solubility while meeting all processing and product quality requirements for WTP HLW glass. Subsequent melter testing showed that this formulation showed no sulfate salt formation even at a waste loading of 38 wt% or at a target sulfur concentration of 1.91 wt% SO_3.

Glass melts were bubbled with gas mixtures that include sulfur to determine the solubility of sulfur in the glass using a procedure previously used with HLW and LAW glasses [18, 33]. The sulfur solubility was measured for four glasses formulated with Hanford HLW high-iron streams and four glasses formulated with waste streams containing high concentrations of bismuth, chromium, aluminum, and aluminum plus sodium specified by ORP. These results were compared to a variety of other glasses subjected to the same sulfur solubility measurement procedure to discern trends in sulfur solubility with glass composition. Despite the difficulty in detecting trends in multi-element glasses, sulfur solubility does appear to increase with increasing alkaline earth elements and boron concentrations. The association of alkali and sulfur solubility appears to be much weaker in the HLW glasses studied in contrast to LAW glasses where Li_2O was beneficial in improving sulfate solubility. The measured sulfur solubility for glass formulated with both high iron and high aluminum wastes demonstrate that sulfur solubility can be increased through changes in glass formulation while maintaining other properties within acceptable ranges.

Melter tests were conducted with three different HLW simulants and associated glass formulations at various feed sulfur concentrations on the DM10 melter. The highest sulfur feed concentrations and waste loadings that could be processed through the DM10 without the formation of secondary sulfate phases were determined. These tests produced over 360 kg of glass from over a metric ton of feed formulated for three different HLW streams: a C106/AY-102 high iron composition, an ORP defined high aluminum composition, and a projected high sulfur stream. In each of the eighteen tests, the bubbling rate was adjusted to achieve a feed rate of 3 kg/hr (about 1300 kg/m^2/day), a complete cold cap, and a target plenum temperature of 550 – 650°C. Glass samples taken throughout the tests from the melt pool and the air-lift discharge were visually examined for secondary phases and analyzed for chemical composition. Glass samples were taken from the melt pool to detect secondary phases on the melt pool surface. Results for the three glass composition are summarized as follows:

HWI-Al-19 (high aluminum waste): The sulfur content of the feed was progressively increased to 1.3 wt% SO_3 on a glass basis, and a measured SO_3 content of 0.8 wt% in the glass product, without any observations of secondary sulfur phases. Testing at higher feed and glass sulfur levels resulted in the formation of secondary phases. Therefore the processing limits for sulfur content appears to be 1.3 and 0.8 wt% SO_3 for the feed and glass, respectively, which is significantly less than the 1.25 wt% SO_3 saturation level for glass measured in the crucible-scale bubbling tests.

HLW-NG-Fe2 (high iron waste): The sulfur content of the feed was decreased progressively from 0.7 to 0.6, 0.5, and 0.4 wt% SO_3 on a glass basis with numerous observations of secondary sulfur phases at the two highest sulfur concentrations and little or no observations of secondary phase at the lower concentrations. The test results indicate that the limiting feed sulfur concentration is about 0.5 wt% SO_3 and the associated level of sulfur in the glass is about 0.35 wt% SO_3, which is significantly less than the 0.83 wt% SO_3 saturation level measured in the crucible-scale bubbling tests.

HLWS-09 (high sulfur waste): The sulfur content of the feed was adjusted both by increasing the ratio of the sulfur-containing waste to the additives and by adding sulfuric acid to the nominal feed composition. The feed concentration of sulfur was increased to 1.63 wt% SO_3 at 38% waste loading and 1.91 wt% SO_3 at the nominal waste loading without the formation of secondary sulfate phases. The concentration of sulfur in the glass increased to 1.2 wt% SO_3 at the high waste loading and 1.6 wt% SO_3 at the nominal waste loading. Thus, the limit for sulfur in the glass is greater than 1.6 wt% SO_3, which is consistent with the 1.78 wt% SO_3 saturation level measured in the crucible-scale bubbling tests. The composition was also shown to be robust with respect to formation of secondary phases resulting from changes in glass composition resulting from changes in waste loading. The very high sulfur tolerance of this formulation, which rivals that of the best LAW formulations, is noteworthy, particularly in comparison to the present WTP limit of for HLW glass of 0.5 wt% SO_3.

6.1 Recommendations for Future Work

The results of the testing presented herein show the range in sulfur solubility in HLW glasses and the potential for increasing the sulfur solubility through glass formulation. The results also demonstrate that although sulfur solubility in glass defines the equilibrium amount of sulfur that can be retained in glass, solubility is not the only factor determining secondary phase formation while processing on a continuously fed melter since kinetic factors also play an important role. The test results further demonstrate that it is possible to develop HLW glass formulations that can tolerate significantly higher levels of sulfur than would be allowed by the present WTP limit of 0.5 wt% SO_3 in HLW glass. This work illustrates the potential for significant reductions in HLW canister count and HLW processing duration for sulfur-limited HLW streams, which are projected to account for some 22% of the HLW batches in the WTP mission [51]. Further work that is recommended in order to develop and demonstrate this potential for implementation into the WTP is outlined below.

- *Increase Sulfur Solubility in Glass through Formulation Enhancements*: Glass formulations with higher sulfur solubility, and thus higher waste loading, should be developed for HLW streams that are currently projected to be limited by sulfur solubility. This strategy would entail developing an approach with additive blends that can be applied to projected future waste streams with high sulfur contents. A model that relates sulfur solubility to glass composition would be a useful tool for implementing these enhancements into the WTP facility and it is recommended that such a model be developed. Increases in sulfur solubility through glass formulation must be balanced against other benefits of glass formulation enhancements such as glass production rate and compliance with relevant glass processing and product quality requirements for the WTP.

- *Identification of Kinetic Factors Contributing to Secondary Sulfate Phase Formation*: Melter testing should be performed to fully determine the factors responsible for secondary phase formation in HLW glasses at sulfur contents significantly below the measured sulfur solubility limit. Operational strategies need to be identified to mitigate such secondary sulfur phase formation. In particular, the interplay between processing rate and sulfate salt formation needs to be investigated.

- *Other WTP HLW Feed Types*: The present testing was based on a limited number of HLW compositions from the Hanford tanks. The work should be extended to address the full range of high-S HLW feeds expected to be processed at the WTP. The HLW compositions evaluated to date also contain very limited amounts of nitrates and organic carbon.

- *Scale-Up Testing*: Since the formation of secondary sulfur phases is partly related to kinetic factors and can be thus affected by melt surface area, processing rate, and melt pool bubbling, larger scale testing should be performed to confirm the results from the crucible and the DM10 systems. Scale-up testing is also needed to resolve the observed processing rate assessments from the VGF and DM10 melter for the HLWS-09 feed. Such tests could be performed on the DM100 melter system with more limited testing on the DM1200 system.

- *Material Corrosion Tests*: Very little testing has been done to understand the failure mechanism of metallic melter components (e.g., bubblers) in high-S HLW glass melts. Such tests are needed to determine the useful life of such components and to develop mitigation strategies, if needed. In particular, whereas the LAW bubbler design specifically considered the effects of high-sulfur feeds, there was no such consideration for the HLW bubbler design.

SECTION 7.0
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Table 2.1. Compositional Summary (wt% Oxide Basis) of the C-106/AY-102 Actual Waste, AW-101 Cesium-Eluate, Blended Waste, and the High-Iron HLW Simulant.

Oxide	Analyzed C-106/AY-102 Solid	Analyzed AW-101 Cesium-Eluate	Blended C-106/AY-102 Actual Waste	High-Iron HLW Simulant
Ag_2O	0.50%	—	0.50%	—
Al_2O_3	13.17%	—	13.16%	13.29%
B_2O_3	0.70%	33.18%	0.73%	0.74%
BaO	0.20%	1.68%	0.20%	0.20%
CaO	1.23%	—	1.23%	1.24%
CdO	0.03%	0.38%	0.03%	—
Ce_2O_3	0.27%	4.91%	0.27%	0.27%
Cr_2O_3	0.60%	0.69%	0.60%	0.61%
Cs_2O	—	3.36%	0.00%	0.00%
CuO	0.09%	2.57%	0.09%	—
Fe_2O_3	37.78%	0.41%	37.74%	38.12%
Gd_2O_3	0.02%	—	0.02%	—
K_2O	0.03%	—	0.03%	—
La_2O_3	0.20%	0.85%	0.20%	0.22%
Li_2O	0.11%	7.34%	0.12%	0.12%
MgO	0.39%	—	0.39%	0.39%
MnO	7.61%	—	7.60%	7.68%
MoO_3	0.09%	—	0.09%	—
Na_2O	14.48%	35.73%	14.50%	14.68%
NiO	1.11%	1.36%	1.11%	1.12%
P_2O_5	1.51%	—	1.51%	1.53%
PbO	1.46%	—	1.46%	1.47%
SO_3	0.51%	—	0.51%	0.52%
Sb_2O_5	0.11%	—	0.11%	—
SiO_2	14.28%	—	14.27%	14.41%
SnO_2	0.16%	6.83%	0.17%	0.17%
SrO	0.46%	0.71%	0.46%	0.46%
TiO_2	0.09%	—	0.09%	—
U_3O_8	1.40%	—	1.40%	—
V_2O_5	0.04%	—	0.04%	—
ZnO	0.08%	—	0.08%	0.08%
ZrO_2	1.25%	—	1.25%	2.68%
TOTAL	100.0%	100.0%	100.0%	100.0%

— Empty data field

Table 2.2. Compositional Summary of the High-Iron HLW Simulant, Reference Glass HLW04-09, and Target Glass for Previous Melter Tests [16, 27, 28].

Oxide (wt%)	High-Iron HLW Simulant	HLW04-09	Target Glass for Previous Melter Tests based on HLW04-09 [16, 27]	Target Glass for Previous Melter Tests with Enhanced HLW-NG-Fe2 Formulation [28]
Ag_2O	—	0.19%	—	—
Al_2O_3	13.29%	4.88%	4.89%	5.58%
B_2O_3	0.74%	10.27%	10.27%	13.81%
BaO	0.20%	0.07%	0.07%	0.08%
CaO	1.24%	0.46%	0.46%	0.52%
CdO	—	0.01%	—	—
Ce_2O_3	0.27%	0.10%	0.10%	0.10%
Cr_2O_3	0.61%	0.22%	0.22%	0.26%
CuO	—	0.03%	—	—
Fe_2O_3	38.12%	14.01%	14.03%	16.01%
Gd_2O_3	—	0.01%	—	—
K_2O	—	0.01%	—	—
La_2O_3	0.22%	0.07%	0.08%	0.08%
Li_2O	0.12%	2.64%	2.64%	1.55%
MgO	0.39%	0.14%	0.14%	0.16%
MnO	7.68%	2.82%	2.82%	3.23%
MoO_3	—	0.03%	—	—
Na_2O	14.68%	12.53%	12.55%	14.17%
NiO	1.12%	0.41%	0.41%	0.47%
P_2O_5	1.53%	0.56%	0.56%	0.64%
PbO	1.47%	0.54%	0.54%	0.62%
SO_3	0.52%	0.19%	0.19%	0.22%
Sb_2O_5	—	0.04%	—	—
SiO_2	14.41%	47.75%	47.75%	41.05%
SnO_2	0.17%	0.06%	0.06%	0.07%
SrO	0.46%	0.17%	0.17%	0.19%
TiO_2	—	0.03%	—	—
U_3O_8	—	0.52%	—	—
V_2O_5	—	0.01%	—	—
ZnO	0.08%	0.73%	1.03%	0.03%
ZrO_2	2.68%	0.46%	0.98%	1.13%
TOTAL	100.0%	100.0%	100.0%	100.0%
Volatiles (g/100 g oxide	—	—	—	—
Carbonate	4.650	—	—	—
Nitrite	0.012	—	—	—
Nitrate	0.784	—	—	—
TOC	0.026	—	—	—

— Empty data field

Table 2.3. Analyzed Compositions of AZ-101 Envelope D Waste.

Analyte	AZ-101 Solid (µg/g dry solid)	Oxide$^{\#}$	Analyzed AZ-101 Solid (wt%)
Ag	902	Ag_2O	0.12%
Al	99873	Al_2O_3	23.71%
As	—	As_2O_3	—
B	91	B_2O_3	0.04%
Ba	1510	BaO	0.21%
Be	26	BeO	0.01%
Bi	150	Bi_2O_3	0.02%
Ca	7505	CaO	1.32%
Cd	14500	CdO	2.08%
Ce	5240	Ce_2O_3	0.77%
Cl	703	Cl	0.09%
Co	128	CoO	0.02%
Cr	2285	Cr_2O_3	0.42%
Cs	—	Cs_2O	—
Cu	584	CuO	0.09%
F	390	F	0.05%
Fe	202384	Fe_2O_3	36.35%
K	2000	K_2O	0.30%
La	5808	La_2O_3	0.86%
Li	115	Li_2O	0.03%
Mg	1540	MgO	0.32%
Mn	5364	MnO_2	1.07%
Mo	67	MoO_3	0.01%
Na	54545	Na_2O	9.24%
Nd	4290	Nd_2O_3	0.63%
Ni	9992	NiO	1.60%
P	4505	P_2O_5	1.30%
Pb	1728	PbO	0.23%
Pd	2300	PdO	0.33%
Rh	513	Rh_2O_3	0.08%
Ru	1600	Ru_2O_3	0.25%
SO_4	2410	SO_3	0.25%
Sb	—	Sb_2O_5	—
Se	—	SeO_2	—
Si	13055	SiO_2	3.51%
Sn	3600	SnO_2	0.37%
Sr	3412	SrO	0.51%
Te	—	TeO_2	—
Ti	178	TiO_2	0.04%
U	18500	UO_2	2.64%
Y	385	Y_2O_3	0.06%
Zn	278	ZnO	0.04%
Zr	65050	ZrO_2	11.05%
TOTAL	537186	TOTAL	100.0%

- Empty data field. $^{\#}$ Oxide forms listed are those provided by the WTP Project

Table 2.4. Compositions of the AZ-101 Waste (Oxide Basis) and the HLW Waste Simulant to Produce 100 kg of Waste Oxides (21.5 wt% total solids).

AZ-101 HLW Waste Composition		AZ-101 HLW Waste Simulant	
Waste Oxide	**Wt%**	**Starting Material**	**Target Weight (kg)**[*]
Al_2O_3	24.62%	$Al(OH)_3$	37.995
CaO	1.40%	CaO	1.429
CdO	2.16%	CdO	2.184
Ce_2O_3	0.80%	CeO_2	0.847
Cr_2O_3	0.46%	Cr_2O_3	0.469
Cs_2O	0.50%	CsOH (50% solution)	1.064
Fe_2O_3	37.73%	$Fe(OH)_3$ (13% slurry)	372.255
La_2O_3	0.89%	La_2O_3	0.899
MnO	0.91%	MnO_2	1.127
Na_2O	10.60%	NaOH	10.402
Nd_2O_3	0.65%	Nd_2O_3	0.657
NiO	1.66%	$Ni(OH)_2$	2.135
P_2O_5	1.34%	$FePO_4 \cdot xH_2O$	3.560
SO_3	0.38%	Na_2SO_4	0.682
SiO_2	3.78%	SiO_2	3.808
SnO_2	0.66%	SnO_2	0.667
ZrO_2	11.46%	$Zr(OH)_4 \cdot xH_2O$	29.565
Carbonate	1.20[#]	Na_2CO_3	2.130
Nitrite	0.50[#]	$NaNO_2$	0.769
Nitrate	2.00[#]	$NaNO_3$	2.459
Organic Carbon	0.05[#]	$H_2C_2O_4 \cdot 2H_2O$	0.264
		Water	155.610
Oxide Total	100.00%	TOTAL	630.977

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

Table 2.5. Compositions of Nominal AZ-101 HLW Glass Formulations (wt%).

	AZ-101 Waste			**Glass Composition**		
Oxide [#]	**Actual Blended Waste [41, 43]**	**Next Generation Melter Tests [22]**	**Goethite Melter Tests [29]**	**Crucible Melt [14]**	**Next Generation Melter Tests [22]**	**Goethite Melter Tests [29]**
Ag_2O	0.12%	-	-	0.04%	-	-
Al_2O_3	23.06%	24.58%	24.62%	7.32%	7.80%	7.81%
B_2O_3	0.43%	-	-	10.64%	10.50%	10.50%
BaO	0.21%	-	-	0.07%	-	-
BeO	0.01%	-	-	0.00%	-	-
Bi_2O_3	0.02%	-	-	0.01%	-	-
CaO	1.34%	1.40%	1.40%	0.43%	0.44%	0.44%
CdO	2.02%	2.16%	2.16%	0.64%	0.69%	0.69%
Ce_2O_3	0.75%	0.80%	0.80%	0.24%	0.25%	0.25%
Cl	0.18%	-	-	0.06%	-	-
Cr_2O_3	0.45%	0.46%	0.46%	0.14%	0.15%	0.15%
Cs_2O	0.00%	0.50%	0.50%	0.00%	0.16%	0.16%
CuO	0.09%	-	-	0.03%	-	-
F	0.05%	-	-	0.02%	-	-
Fe_2O_3	35.31%	37.67%	37.73%	11.21%	11.96%	11.98%
K_2O	0.43%	-	-	0.14%	-	-
La_2O_3	0.83%	0.89%	0.89%	0.26%	0.28%	0.28%
Li_2O	0.03%	-	-	3.76%	3.75%	3.75%
MgO	0.31%	-	-	0.10%	-	-
MnO_2	1.04%	0.91%	0.91%	0.33%	0.29%	0.29%
MoO_3	0.01%	-	-	0.00%	-	-
Na_2O	10.80%	10.58%	10.60%	11.93%	11.86%	11.87%
Nd_2O_3	0.61%	0.65%	0.65%	0.19%	0.21%	0.21%
NiO	1.55%	1.66%	1.66%	0.49%	0.53%	0.53%
P_2O_5	1.26%	1.34%	1.34%	0.40%	0.43%	0.43%
PbO	0.23%	-	-	0.07%	-	-
PdO	0.32%	-	-	0.10%	-	-
Rh_2O_3	0.08%	-	-	0.02%	-	-
RuO_2	0.24%	0.15%	-	0.08%	0.05%	-
SO_3	0.37%	0.38%	0.38%	0.12%	0.12%	0.12%
SiO_2	3.80%	3.77%	3.78%	44.71%	44.70%	44.70%
SnO_2	-	0.66%	0.66%	-	0.21%	0.21%
SrO	0.49%	-	-	0.16%	-	-
TiO_2	0.04%	-	-	0.01%	-	-
UO_2	2.76%	-	-	0.88%	-	-
ZnO	0.04%	-	-	2.01%	2.00%	2.00%
ZrO_2	10.72%	11.44%	11.46%	3.40%	3.63%	3.64%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

- Empty data field. # Oxide forms listed are those employed by the WTP Project

Table 2.6. Compositional Summary of Different Waste Streams and Blended Solids for the AZ-102 HLW Simulant.

Feed Constituent	**AZ-102 Solids** FRP02 (lb/day)	**Recycle Stream** PWD01 (lb/day)	**Separation Factor** (fraction remained)	**Cs-Eluate** CNP12 (lb/day)	**Tc-Eluate** TEP12 (lb/day)	**Blended Solids** HLP09b (lb/day)
Ag	7.68E+00	4.17E-21	1.00E+00	-	-	7.68E+00
Al	1.75E+03	1.77E+00	4.20E-01	5.29E-01	2.12E-02	7.36E+02
As	5.19E-01	1.21E-01	1.00E+00	-	-	6.40E-01
B	3.60E+01	3.11E+00	1.00E+00	6.66E-01	6.80E-02	3.98E+01
Ba	6.13E+00	1.64E-04	2.42E-01	-	-	1.48E+00
Be	1.18E-01	0.00E+00	1.00E+00	-	-	1.18E-01
Bi	9.70E-01	2.34E-04	1.00E+00	-	-	9.71E-01
Ca	4.19E+01	8.14E-02	9.88E-01	3.41E-02	2.32E-03	4.15E+01
Cd	2.97E+02	6.19E-04	8.27E-02	-	-	2.46E+01
Ce	8.56E+00	5.88E+00	7.72E-02	-	-	1.11E+00
Cl	4.24E+00	9.42E-02	7.95E-02	-	1.29E-02	3.57E-01
Co	6.82E-01	0.00E+00	1.00E+00	-	-	6.82E-01
Carbonate	5.27E+02	2.24E+00	1.31E-01	-	-	6.91E+01
Cr	2.11E+01	2.15E-01	1.52E-01	6.83E-02	3.32E-03	3.31E+00
Cs	6.82E-01	0.00E+00	1.15E-01	2.73E-01	-	3.52E-01
Cu	2.30E+00	2.37E-44	1.00E+00	2.90E-01	-	2.59E+00
F	8.96E+00	1.27E+00	8.25E-02	-	-	8.44E-01
Fe	2.19E+03	1.41E+00	9.94E-01	1.19E-01	2.22E-02	2.18E+03
Hg	2.01E-01	1.90E-05	1.00E+00	-	-	2.01E-01
K	5.14E+01	6.82E-01	9.29E-02	1.86E+00	4.15E-02	6.74E+00
La	8.09E+01	1.80E-02	9.85E-01	-	-	7.96E+01
Li	9.99E-02	8.15E-01	1.00E+00	-	-	9.15E-01
Mg	1.07E+01	7.28E-06	1.00E+00	-	3.32E-04	1.07E+01
Mn	5.60E+01	8.20E-02	9.99E-01	-	3.32E-04	5.60E+01
Mo	1.22E+00	0.00E+00	1.00E+00	-	-	1.22E+00
Na	7.29E+02	3.59E+02	1.15E-01	1.71E+01	3.32E-01	1.43E+02
Nd	2.96E+01	0.00E+00	1.00E+00	-	-	2.96E+01
Ni	8.84E+01	1.07E-01	9.83E-01	2.56E-01	2.65E-03	8.73E+01
Nitrite	3.13E+02	2.56E-01	7.84E-02	-	-	2.46E+01
Nitrate	7.86E+00	8.21E+02	7.77E-02	4.92E+01	-	1.14E+02
Hydroxide	1.08E+02	3.16E+01	5.97E-01	-	-	8.32E+01
Hydroxide(Bound)	5.74E+03	0.00E+00	7.68E-02	-	-	4.41E+02
Pb	1.63E+01	2.00E-02	1.00E+00	1.19E-01	-	1.64E+01
Pd	9.82E-01	1.95E-09	1.00E+00	-	-	9.82E-01
Phosphate	3.81E+01	5.01E-03	2.20E-01	5.23E-02[@]	2.03E-03[@]	8.43E+00
Pr	5.60E+00	0.00E+00	1.00E+00	-	-	5.60E+00
Rb	8.39E-02	0.00E+00	1.00E+00	-	-	8.39E-02
Rh	5.90E-01	0.00E+00	-[*]	-	-	5.90E-01
Ru	2.63E+00	0.00E+00	-	-	-	0.00E+00
Sb	7.17E-02	0.00E+00	-	-	-	0.00E+00
Se	1.68E-01	0.00E+00	-	-	-	0.00E+00
Si	1.11E+02	6.46E+00	9.97E-01	4.61E-01	9.29E-02	1.18E+02
Sulfate	1.36E+02	2.46E+01	7.69E-02	-	-	1.23E+01
Sr	2.39E+00	0.00E+00	9.58E-01	-	-	2.29E+00
Ta	3.94E-02	0.00E+00	-	-	-	0.00E+00
Te	9.30E-01	0.00E+00	-	-	-	0.00E+00
Th	4.25E+00	0.00E+00	-	-	-	0.00E+00
Ti	6.42E-01	1.39E-03	1.00E+00	-	-	6.43E-01
Tl	3.94E-02	0.00E+00	-	-	-	0.00E+00
TOC	3.90E+01	0.00E+00	7.67E-02	-	-	2.99E+00
U	2.33E+02	0.00E+00	-	6.14E-01	0.00E+00	6.14E-01
V	5.02E-01	0.00E+00	-	-	-	0.00E+00
Y	2.06E+00	0.00E+00	-	-	-	0.00E+00
Zn	1.47E+00	4.71E-01	1.00E+00	5.12E-02	3.32E-04	2.00E+00
Zr	3.26E+02	3.13E-01	9.99E-01	-	-	3.26E+02
TOTAL	**1.30E+04**	**1.26E+03**[#]	-	7.16E+01	6.02E-01	4.69E+03

[*] Analytes with undetermined separation factors are omitted. [#] 1.28E+03 if H^+ is included. [@] Converted from P. "-" Empty data field

Table 2.7. Compositional Summary (Oxide Basis) of the AZ-102 HLW Simulant, Glass Additives, Target Test Glass, and the Reference Glass (HLW98-80) [30].

Wt%	**AZ-102 HLW Simulant**	**Glass Former (as wt% of glass)**	**Melter Test Target Glass**	**HLW98-80**
Ag_2O	--	--	--	0.034%
Al_2O_3	23.10%	--	5.60%	5.590%
B_2O_3	2.13%	12.00%	12.52%	12.529%
CaO	0.97%	--	0.23%	0.233%
CdO	0.47%	--	0.11%	0.114%
Cl	--	--	--	--
Cs_2O	0.21%	--	0.05%	--
F	--	--	--	--
Fe_2O_3	51.80%	--	12.56%	12.530%
K_2O	0.13%	--	0.03%	0.032%
La_2O_3	1.55%	--	0.38%	0.376%
Li_2O	0.03%	3.25%	3.26%	3.260%
MgO	0.30%	--	0.07%	0.073%
MnO^*	1.47%	--	0.36%	0.357%
Na_2O	3.20%	11.25%	12.02%	12.033%
Nd_2O_3	0.68%	--	0.17%	0.165%
NiO	1.85%	--	0.45%	0.447%
P_2O_5	0.10%	--	0.03%	0.024%
PbO	0.29%	--	0.07%	0.070%
SiO_2	4.18%	47.25%	48.26%	48.308%
SO_3	0.17%	--	0.04%	0.041%
ZnO	0.04%	2.00%	2.01%	2.012%
ZrO_2	7.32%	--	1.78%	1.772%
TOTAL	100.0%	75.75%	100.00%	100.000%
Volatiles (g/100 g oxide)				
Carbonate	1.145	--	--	--
Nitrite	0.407	--	--	--
Nitrate	1.883	--	--	--
TOC	0.050	--	--	--

*MnO_2 in Reference [30]

— Empty data field

Table 2.8. Oxide Compositions of Limiting Waste Streams.

Waste Oxides	**Bi Limited**		**Cr Limited**		**Al Limited**		**Al and Na Limited**	
	Actual	**Non-Rad.**	**Actual**	**Non-Rad.**	**Actual**	**Non-Rad.**	**Actual**	**Non-Rad.**
Al_2O_3	22.45%	23.32%	25.53%	27.64%	49.21%	53.27%	43.30%	45.40%
B_2O_3	0.58%	0.60%	0.53%	0.57%	0.39%	0.42%	0.74%	0.78%
CaO	1.61%	1.67%	2.47%	2.67%	2.21%	2.39%	1.47%	1.54%
Fe_2O_3	13.40%	13.92%	13.13%	14.21%	12.11%	13.11%	5.71%	5.99%
Li_2O	0.31%	0.32%	0.36%	0.39%	0.35%	0.38%	0.15%	0.16%
MgO	0.82%	0.85%	0.16%	0.17%	0.24%	0.26%	0.44%	0.46%
Na_2O	12.97%	13.47%	20.09%	21.75%	7.35%	7.96%	25.79%	27.04%
SiO_2	12.04%	12.51%	10.56%	11.43%	10.05%	10.88%	6.22%	6.52%
TiO_2	0.30%	0.31%	0.01%	0.01%	0.02%	0.02%	0.35%	0.37%
ZnO	0.31%	0.32%	0.25%	0.27%	0.17%	0.18%	0.36%	0.38%
ZrO_2	0.40%	0.42%	0.11%	0.12%	0.81%	0.88%	0.25%	0.26%
SO_3	0.91%	0.95%	1.52%	1.65%	0.41%	0.44%	0.44%	0.46%
Bi_2O_3	12.91%	13.41%	7.29%	7.89%	2.35%	2.54%	2.35%	2.46%
ThO_2	0.25%	Omitted	0.04%	Omitted	0.37%	Omitted	0.04%	Omitted
Cr_2O_3	1.00%	1.04%	3.07%	3.32%	1.07%	1.16%	1.44%	1.51%
K_2O	0.89%	0.92%	0.37%	0.40%	0.29%	0.31%	1.34%	1.40%
U_3O_8	3.48%	Omitted	7.59%	Omitted	7.25%	Omitted	4.58%	Omitted
BaO	0.02%	0.02%	0.03%	0.03%	0.11%	0.12%	0.06%	0.06%
CdO	0.00%	0.00%	0.01%	0.01%	0.05%	0.05%	0.02%	0.02%
NiO	3.71%	3.85%	1.06%	1.15%	0.82%	0.89%	0.20%	0.21%
PbO	0.48%	0.50%	0.48%	0.52%	0.84%	0.91%	0.18%	0.19%
P_2O_5	9.60%	9.97%	3.34%	3.62%	2.16%	2.34%	4.10%	4.30%
F-	1.58%	1.64%	2.00%	2.17%	1.37%	1.48%	0.46%	0.48%
Total	100.00%	100.0%	100.00%	100.0%	100.00%	100.0%	100.00%	100.0%

Table 2.9. Compositions of the Bi-Limited Waste (Oxide Basis) and the HLW Waste Simulant to Produce 100 kg of Waste Oxides (20 wt% suspended solids).

Bi-Limited Waste Composition		Bi-Limited HLW Waste Simulant	
Waste Oxide	**Wt%**	**Starting Materials**	**Target Weight (kg)** *
Al_2O_3	22.45%	Al_2O_3	22.677
B_2O_3	0.58%	H_3BO_3	1.041
CaO	1.61%	CaO	1.643
Fe_2O_3	13.40%	$Fe(OH)_3$ (13% Slurry)	26.752
Li_2O	0.31%	Li_2CO_3	0.786
MgO	0.82%	MgO	0.863
Na_2O	12.97%	NaOH	11.108
SiO_2	12.04%	SiO_2	12.162
TiO_2	0.30%	TiO_2	0.303
ZnO	0.31%	ZnO	0.313
ZrO_2	0.40%	$Zr(OH)_4 \cdot xH_2O$	1.034
SO_3	0.91%	Na_2SO_4	1.632
Bi_2O_3	12.91%	Bi_2O_3	13.040
ThO_2	0.25%	Omitted	
Cr_2O_3	1.00%	$Cr_2O_3 \cdot 1.5H_2O$	1.190
K_2O	0.89%	KNO_3	1.940
U_3O_8	3.48%	Omitted	
BaO	0.02%	$BaCO_3$	0.026
CdO	0.00%	CdO	0.000
NiO	3.71%	$Ni(OH)_2$	4.771
PbO	0.48%	PbO	0.485
P_2O_5	9.60%	$FePO_4 \cdot xH_2O$	25.501
F	1.58%	NaF	3.510
Carbonate	1.20#	Na_2CO_3	1.011
Nitrite	0.50#	$NaNO_2$	0.769
Nitrate	2.00#	$NaNO_3$	1.141
Organic Carbon	0.05#	$H_2C_2O_4 \cdot 2H_2O$	0.264
—	—	Water	353.500
TOTAL	100.0%	TOTAL	487.463

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

Table 2.10. Compositions of the Al-Limited Waste (Oxide Basis) and the HLW Waste Simulant to Produce 100 kg of Waste Oxides (20 wt% suspended solids).

Al-Limited Waste Composition		Al-Limited HLW Waste Simulant	
Waste Oxide	**Wt%**	**Starting Materials**	**Target Weight (kg)** *
Al_2O_3	49.21%	Al_2O_3	49.707
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%	Omitted	
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%	Omitted	
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
TOTAL	100.0%	TOTAL	469.478

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

Table 2.11. Compositions of the Al- and Na-Limited Waste (Oxide Basis) and the HLW Waste Simulant to Produce 100 kg of Waste Oxides (20 wt% suspended solids).

Al- and Na-Limited Waste Composition		Al- and Na-Limited HLW Waste Simulant	
Waste Oxide	**Wt%**	**Starting Materials**	**Target Weight (kg)** *
Al_2O_3	43.30%	Al_2O_3	43.737
B_2O_3	0.74%	H_3BO_3	1.328
CaO	1.47%	CaO	1.500
Fe_2O_3	5.71%	$Fe(OH)_3$ (13% Slurry)	11.292
Li_2O	0.15%	Li_2CO_3	0.380
MgO	0.44%	MgO	0.463
Na_2O	25.79%	NaOH	31.057
SiO_2	6.22%	SiO_2	6.283
TiO_2	0.35%	TiO_2	0.354
ZnO	0.36%	ZnO	0.364
ZrO_2	0.25%	$Zr(OH)_4 \cdot xH_2O$	0.646
SO_3	0.44%	Na_2SO_4	0.789
Bi_2O_3	2.35%	Bi_2O_3	2.374
ThO_2	0.04%	Omitted	
Cr_2O_3	1.44%	$Cr_2O_3 \cdot 1.5H_2O$	1.713
K_2O	1.34%	KNO_3	2.921
U_3O_8	4.58%	Omitted	
BaO	0.06%	$BaCO_3$	0.078
CdO	0.02%	CdO	0.020
NiO	0.20%	$Ni(OH)_2$	0.257
PbO	0.18%	PbO	0.182
P_2O_5	4.10%	$FePO_4 \cdot xH_2O$	10.891
F	0.46%	NaF	1.022
Carbonate	1.20#	Na_2CO_3	1.554
Nitrite	0.50#	$NaNO_2$	0.769
Nitrate	2.00#	$NaNO_3$	0.325
Organic Carbon	0.05#	$H_2C_2O_4 \cdot 2H_2O$	0.264
—	—	Water	381.400
TOTAL	100.0%	TOTAL	501.964

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

Table 2.12. Composition and Properties of Bismuth Limited Waste and Glass Formulation at 50% Waste Loading Used in Melter Tests (wt%).

-	Bi-Limited Waste*	Waste in Glass	Glass Forming Additives	Target Glass HLW-E-Bi-6
Al_2O_3	23.31	11.66	-	11.66
B_2O_3	0.60	0.30	11.00	11.30
BaO	0.02	0.01	-	0.01
Bi_2O_3	13.41	6.71	-	6.71
CaO	1.67	0.84	-	0.84
Cr_2O_3	1.04	0.52	-	0.52
F	1.64	0.82	-	0.82
Fe_2O_3	13.92	6.96	-	6.96
K_2O	0.92	0.46	-	0.46
Li_2O	0.32	0.16	-	0.16
MgO	0.85	0.43	-	0.43
Na_2O	13.47	6.74	9.00	15.74
NiO	3.85	1.93	-	1.93
P_2O_5	9.97	4.99	-	4.99
PbO	0.50	0.25	-	0.25
SiO_2	12.51	6.26	30.00	36.26
TiO_2	0.31	0.16	-	0.16
SO_3	0.95	0.48	-	0.48
ZnO	0.32	0.16	-	0.16
ZrO_2	0.42	0.21	-	0.21
Sum	100	50	50	100

* Renormalized from Ref. [21] after removal of radioactive components

Viscosity @1150°C, P			96
Conductivity @1150°C, S/cm			0.47
Crystal Content, As Melted			Trace
Crystal Content, 72 hr at 950°C			~1.8vol%
TCLP			Pass
PCT, g/L	-	DWPF-EA	HLW-E-Bi-6
	B	16.7	0.49
	Li	9.6	0.18
	Na	13.3	0.53

- Empty data field

Table 2.13. Composition and Properties of Aluminum Limited Waste and Glass Formulation HLW-E-Al-27 at 45% Waste Loading Used in Melter Tests (wt%).

-	**Al-Limited Waste***	**Waste in Glass**	**Glass Forming Additives**	**Target Glass HLW-E-Al-27**
Al_2O_3	53.27	23.97	-	23.97
B_2O_3	0.42	0.19	15.00	15.19
BaO	0.12	0.05	-	0.05
Bi_2O_3	2.54	1.14	-	1.14
CaO	2.39	1.08	5.00	6.08
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
SiO_2	10.88	4.90	25.60	30.50
TiO_2	0.02	0.01	-	0.01
SO_3	0.44	0.20	-	0.20
ZnO	0.18	0.08	-	0.08
ZrO_2	0.88	0.39	-	0.39
Sum	100.00	45.00	55.00	100.00

* Renormalized from Ref. [21] after removal of radioactive components

Viscosity @1150°C, P			46
Conductivity @1150°C, S/cm			0.26
Crystal Content, As Melted			Trace
Crystal Content, 72 hr at 950°C			~1.0 vol%
Crystal Content, CCC			~1.9 vol%
TCLP			Pass
PCT, g/L	-	DWPF-EA	HLW-E-Al-27
	B	16.7	0.27
	Li	9.6	0.44
	Na	13.3	0.30

- Empty data field

Table 2.14. 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. [21] after removal of radioactive components.
\# The sum does not equal to 100.00 because of rounding of decimals.

Viscosity @1150°C, P			33
Conductivity @1150°C, 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	0.65
	Li	9.6	0.79
	Na	13.3	0.62

- Empty data field

Table 2.15. Composition and Properties of Aluminum-Plus-Sodium-Limited Waste and Glass Formulation at 47% Waste Loading Used in Melter Tests (wt%).

-	Al-Na Limited Waste*	Waste in Glass	Glass Forming Additives	Target Glass HLW-E-ANa-22
Al_2O_3	45.40	21.34	0.00	21.34
B_2O_3	0.78	0.37	18.00	18.37
BaO	0.06	0.03	0.00	0.03
Bi_2O_3	2.46	1.16	0.00	1.16
CaO	1.54	0.72	0.00	0.72
CdO	0.02	0.01	0.00	0.01
Cr_2O_3	1.51	0.71	0.00	0.71
F	0.48	0.23	0.00	0.23
Fe_2O_3	5.99	2.82	0.00	2.82
K_2O	1.41	0.66	0.00	0.66
Li_2O	0.16	0.08	3.50	3.58
MgO	0.46	0.22	0.00	0.22
Na_2O	27.04	12.71	0.00	12.71
NiO	0.21	0.10	0.00	0.10
P_2O_5	4.30	2.02	0.00	2.02
PbO	0.19	0.09	0.00	0.09
SiO_2	6.52	3.06	31.50	34.56
TiO_2	0.37	0.17	0.00	0.17
SO_3	0.46	0.22	0.00	0.22
ZnO	0.38	0.18	0.00	0.18
ZrO_2	0.26	0.12	0.00	0.12
Sum	100.00	47.00	53.00	100.00

* Renormalized from Ref. [21] after removal of radioactive components

Viscosity @1150°C, P			60
Conductivity @1150°C, S/cm			0.38
Crystal Content, As Melted			Trace
Crystal Content, 72 hr at 950°C			~0.3 vol %
Crystal Content, CCC			~0.5 vol %
TCLP			Pass
PCT, g/L	-	DWPF-EA	HLW-E-ANa-22
	B	16.7	2.55
	Li	9.6	2.09
	Na	13.3	1.18

- Empty data field

Table 2.16. Composition (Oxide wt%) of HLW High Sulfur Simulant.

Oxide	HLW Composition from HTWOS Model Run	Normalized HLW Simulant Composition
Al_2O_3	10.46%	10.80%
B_2O_3	0.14%	0.14%
Bi_2O_3	6.76%	6.98%
CaO	1.57%	1.62%
Cr_2O_3	1.10%	1.14%
F	2.23%	2.30%
Fe_2O_3	6.34%	6.55%
K_2O	2.34%	2.41%
La_2O_3	1.91%	1.98%
MgO	0.71%	0.73%
MnO	3.72%	3.84%
Na_2O	34.98%	36.12%
NiO	4.57%	4.71%
P_2O_5	10.64%	10.99%
PbO	0.32%	0.33%
SO_3	4.15%	4.29%*
SiO_2	4.45%	4.60%*
TiO_2	0.14%	0.14%
ZrO_2	0.31%	0.32%
TOTAL	96.83%	100.0%

* HLW simulant composition used in crucible melts contained 4.60 wt% SO_3 qnd 4.29 wt% SiO_2

Table 2.17. Composition of HLW Simulant to Produce 100 kg of Waste Oxide (21.50 wt% total solids).

Starting Materials	**Target Weight (kg)***
$Al(OH)_3$	17.041
H_3BO_3	0.260
Bi_2O_3	7.053
CaO	1.650
Cr_2O_3	1.160
NaF	5.112
$Fe(OH)_3$ (13% slurry)	67.379
K_2CO_3	3.596
La_2O_3	1.997
MgO	0.754
MnO	3.876
$NaOH$	14.686
$Ni(OH)_2$	6.063
Na_3PO_4	25.897
PbO	0.334
Na_2SO_4	7.692
SiO_2	4.646
TiO_2	0.146
$Zr(OH)_4 \cdot xH_2O$ (50%)	0.836
Na_2CO_3	5.526
$NaNO_2$	0.019
$NaNO_3$	1.080
$H_2C_2O_4 \cdot 2H_2O$	0.138
Water	371.200
TOTAL	548.14

*Target weights adjusted for assay information of starting materials

Table 2.18. Waste Loadings, Glass-Forming additives, and Target Compositions of High Sulfur HLW Glasses.

	HLWS-01	HLWS-02	HLWS-03	HLWS-04	HLWS-05
Waste Loading	26.50%	26.50%	26.50%	28.00%	28.00%
Al_2O_3	9.50%	8.50%	9.50%	20.50%	20.50%
B_2O_3	17.00%	16.50%	15.00%	18.50%	20.00%
CaO	0.00%	0.00%	0.00%	4.00%	2.00%
Li_2O	5.00%	4.50%	5.00%	3.00%	3.50%
SiO_2	42.00%	44.00%	42.00%	26.00%	26.00%
V_2O_5	0.00%	0.00%	2.00%	0.00%	0.00%
ZrO_2	9.50%	8.50%	9.50%	20.50%	0.00%
Glass ID / Composition	**HLWS-01**	**HLWS-02**	**HLWS-03**	**HLWS-04**	**HLWS-05**
Al_2O_3	12.363%	11.363%	12.363%	23.525%	23.525%
B_2O_3	17.038%	16.538%	15.038%	18.541%	20.041%
Bi_2O_3	1.850%	1.850%	1.850%	1.955%	1.955%
CaO	0.429%	0.429%	0.429%	4.453%	2.453%
Cr_2O_3	0.301%	0.301%	0.301%	0.318%	0.318%
F	0.610%	0.610%	0.610%	0.644%	0.644%
Fe_2O_3	1.735%	1.735%	1.735%	1.833%	1.833%
K_2O	0.640%	0.640%	0.640%	0.676%	0.676%
La_2O_3	0.524%	0.524%	0.524%	0.554%	0.554%
Li_2O	5.000%	4.500%	5.000%	3.000%	3.500%
MgO	0.194%	0.194%	0.194%	0.205%	0.205%
MnO	1.017%	1.017%	1.017%	1.074%	1.074%
Na_2O	9.572%	9.572%	9.572%	10.114%	10.114%
NiO	1.249%	1.249%	1.249%	1.320%	1.320%
P_2O_5	2.912%	2.912%	2.912%	3.076%	3.076%
PbO	0.088%	0.088%	0.088%	0.093%	0.093%
SO_3	1.219%	1.219%	1.219%	1.288%	1.288%
SiO_2	43.137%	45.137%	43.137%	27.201%	27.201%
TiO_2	0.038%	0.038%	0.038%	0.040%	0.040%
V_2O_5	0.000%	0.000%	2.000%	0.000%	0.000%
ZrO_2	0.086%	0.086%	0.086%	0.091%	0.091%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

Table 2.18. Waste Loadings, Glass-Forming additives, and Target Compositions of High Sulfur HLW Glasses (Continued).

	HLWS-06	**HLWS-07**	**HLWS-08**	**HLWS-09**	**HLWS-10**
Waste Loading	26.50%	26.50%	28.00%	28.00%	26.50%
Al_2O_3	9.50%	9.50%	20.50%	5.00%	9.50%
B_2O_3	13.00%	11.00%	12.00%	8.50%	11.00%
CaO	4.00%	4.00%	6.00%	8.00%	6.00%
Li_2O	5.00%	5.00%	5.00%	5.00%	5.00%
SiO_2	42.00%	42.00%	28.50%	40.00%	40.00%
V_2O_5	0.00%	2.00%	0.00%	2.00%	2.00%
ZrO_2	0.00%	0.00%	0.00%	3.50%	0.00%
Glass ID Composition	**HLWS-06**	**HLWS-07**	**HLWS-08**	**HLWS-09**	**HLWS-10**
Al_2O_3	12.363%	12.363%	23.525%	8.025%	12.363%
B_2O_3	13.038%	11.038%	12.041%	8.541%	11.038%
Bi_2O_3	1.850%	1.850%	1.955%	1.955%	1.850%
CaO	4.429%	4.429%	6.453%	8.453%	6.429%
Cr_2O_3	0.301%	0.301%	0.318%	0.318%	0.301%
F	0.610%	0.610%	0.644%	0.644%	0.610%
Fe_2O_3	1.735%	1.735%	1.833%	1.833%	1.735%
K_2O	0.640%	0.640%	0.676%	0.676%	0.640%
La_2O_3	0.524%	0.524%	0.554%	0.554%	0.524%
Li_2O	5.000%	5.000%	5.000%	5.000%	5.000%
MgO	0.194%	0.194%	0.205%	0.205%	0.194%
MnO	1.017%	1.017%	1.074%	1.074%	1.017%
Na_2O	9.572%	9.572%	10.114%	10.114%	9.572%
NiO	1.249%	1.249%	1.320%	1.320%	1.249%
P_2O_5	2.912%	2.912%	3.076%	3.076%	2.912%
PbO	0.088%	0.088%	0.093%	0.093%	0.088%
SO_3	1.219%	1.219%	1.288%	1.288%	1.219%
SiO_2	43.137%	43.137%	29.701%	41.201%	41.137%
TiO_2	0.038%	0.038%	0.040%	0.040%	0.038%
V_2O_5	0.000%	2.000%	0.000%	2.000%	2.000%
ZrO_2	0.086%	0.086%	0.091%	3.591%	0.086%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

Table 2.18. Waste Loadings, Glass-Forming additives, and Target Compositions of High Sulfur HLW Glasses (Continued).

	HLWS-11	HLWS-12	HLWS-13	HLWS-14	HLWS-15
Waste Loading	26.50%	26.50%	29.50%	30.50%	32.50%
Al_2O_3	9.50%	9.50%	10.00%	20.00%	20.00%
B_2O_3	11.00%	11.00%	9.50%	19.00%	16.00%
CaO	4.00%	4.00%	2.00%	2.00%	2.00%
Li_2O	5.00%	6.00%	5.00%	2.50%	3.50%
SiO_2	40.00%	41.00%	42.00%	26.00%	26.00%
V_2O_5	4.00%	2.00%	2.00%	0.00%	0.00%
ZrO_2	0.00%	0.00%	0.00%	0.00%	0.00%
Glass ID Composition	**HLWS-11**	**HLWS-12**	**HLWS-13**	**HLWS-14**	**HLWS-15**
Al_2O_3	12.363%	12.363%	13.187%	23.295%	23.511%
B_2O_3	11.038%	11.038%	9.543%	19.044%	16.047%
Bi_2O_3	1.850%	1.850%	2.060%	2.130%	2.269%
CaO	4.429%	4.429%	2.477%	2.493%	2.526%
Cr_2O_3	0.301%	0.301%	0.335%	0.347%	0.370%
F	0.610%	0.610%	0.679%	0.702%	0.748%
Fe_2O_3	1.735%	1.735%	1.931%	1.996%	2.127%
K_2O	0.640%	0.640%	0.712%	0.736%	0.784%
La_2O_3	0.524%	0.524%	0.583%	0.603%	0.642%
Li_2O	5.000%	6.000%	5.000%	2.500%	3.500%
MgO	0.194%	0.194%	0.216%	0.223%	0.238%
MnO	1.017%	1.017%	1.132%	1.170%	1.247%
Na_2O	9.572%	9.572%	10.656%	11.017%	11.739%
NiO	1.249%	1.249%	1.391%	1.438%	1.532%
P_2O_5	2.912%	2.912%	3.241%	3.351%	3.571%
PbO	0.088%	0.088%	0.098%	0.101%	0.107%
SO_3	1.219%	1.219%	1.357%	1.403%	1.495%
SiO_2	41.137%	42.137%	43.265%	27.308%	27.394%
TiO_2	0.038%	0.038%	0.043%	0.044%	0.047%
V_2O_5	4.000%	2.000%	2.000%	0.000%	0.000%
ZrO_2	0.086%	0.086%	0.095%	0.099%	0.105%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

Table 2.18. Waste Loadings, Glass-Forming Additives, and Target Compositions of High Sulfur HLW Glasses (Continued).

	HLWS-16	HLWS-17	HLWS-18	HLWS-19	HLWS-20
Waste Loading	28.00%	32.00%	34.00%	30.00%	30.50%
Al_2O_3	20.50%	9.00%	9.00%	9.50%	19.00%
B_2O_3	18.50%	9.00%	8.00%	9.50%	18.50%
CaO	0.00%	3.00%	2.00%	0.00%	0.00%
Li_2O	4.00%	4.00%	4.00%	5.00%	4.00%
SiO_2	27.00%	41.00%	41.00%	42.00%	26.00%
V_2O_5	2.00%	2.00%	2.00%	4.00%	2.00%
ZrO_2	0.00%	0.00%	0.00%	0.00%	0.00%

Glass ID / **Composition**	HLWS-16	HLWS-17	HLWS-18	HLWS-19	HLWS-20
Al_2O_3	23.525%	12.457%	12.673%	12.741%	22.295%
B_2O_3	18.541%	9.046%	8.049%	9.543%	18.544%
Bi_2O_3	1.955%	2.234%	2.374%	2.095%	2.130%
CaO	0.453%	3.517%	2.550%	0.485%	0.493%
Cr_2O_3	0.318%	0.364%	0.387%	0.341%	0.347%
F	0.644%	0.736%	0.782%	0.690%	0.702%
Fe_2O_3	1.833%	2.095%	2.225%	1.964%	1.996%
K_2O	0.676%	0.772%	0.821%	0.724%	0.736%
La_2O_3	0.554%	0.633%	0.672%	0.593%	0.603%
Li_2O	4.000%	4.000%	4.000%	5.000%	4.000%
MgO	0.205%	0.234%	0.249%	0.220%	0.223%
MnO	1.074%	1.228%	1.305%	1.151%	1.170%
Na_2O	10.114%	11.559%	12.281%	10.836%	11.017%
NiO	1.320%	1.509%	1.603%	1.414%	1.438%
P_2O_5	3.076%	3.516%	3.736%	3.296%	3.351%
PbO	0.093%	0.106%	0.112%	0.099%	0.101%
SO_3	1.288%	1.472%	1.564%	1.380%	1.403%
SiO_2	28.201%	42.372%	42.458%	43.287%	27.308%
TiO_2	0.040%	0.046%	0.049%	0.043%	0.044%
V_2O_5	2.000%	2.000%	2.000%	4.000%	2.000%
ZrO_2	0.091%	0.104%	0.110%	0.097%	0.099%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

Table 2.19. Compositions of HLWS Glasses (wt%) Analyzed by XRF.

Oxide	HLWS-01	HLWS-02	HLWS-03	HLWS-04	HLWS-05
Al_2O_3	12.53%	11.56%	12.50%	23.31%	24.28%
B_2O_3(1)	**17.04%**	**16.54%**	**15.04%**	**18.54%**	**20.04%**
Bi_2O_3	2.01%	2.12%	2.03%	2.06%	2.20%
CaO	0.44%	0.46%	0.44%	4.43%	2.60%
Cr_2O_3	0.24%	0.28%	0.40%	0.30%	0.29%
F(1)	**0.61%**	**0.61%**	**0.61%**	**0.64%**	**0.64%**
Fe_2O_3	1.80%	1.86%	1.80%	1.86%	1.90%
K_2O	0.57%	0.63%	0.61%	0.58%	0.62%
La_2O_3	0.62%	0.75%	0.60%	0.58%	0.65%
Li_2O(1)	**5.00%**	**4.50%**	**5.00%**	**3.00%**	**3.50%**
MgO	0.19%	0.19%	0.21%	0.24%	0.17%
MnO	0.97%	1.11%	1.00%	1.01%	1.27%
Na_2O	9.90%	9.54%	9.98%	10.74%	10.11%
NiO	1.39%	1.38%	1.36%	1.43%	1.53%
P_2O_5	3.24%	3.19%	3.19%	3.29%	3.34%
PbO	0.11%	0.11%	0.09%	0.00%	0.10%
SO_3	0.94%	0.85%	0.89%	1.02%	1.02%
SiO_2	42.25%	44.05%	42.17%	26.81%	25.57%
TiO_2	0.06%	0.05%	0.05%	0.06%	0.05%
V_2O_5	—(2)	—	1.93%	—	—
ZrO_2	0.09%	0.11%	0.09%	0.09%	0.11%
TOTAL	100.0%	99.9%	100.0%	100.0%	100.0%

(1) B_2O_3, F, and Li_2O are not analyzed by XRF; target values (boldface) are used.
(2) — Empty data field (components not present in glass).

Table 2.19. Compositions of HLWS Glasses (wt%) Analyzed by XRF (Continued).

Oxide	HLWS-06	HLWS-07	HLWS-08	HLWS-09	HLWS-10
Al_2O_3	12.67%	12.30%	23.44%	8.04%	12.46%
B_2O_3⁽¹⁾	**13.04%**	**11.04%**	**12.04%**	**8.54%**	**11.04%**
Bi_2O_3	2.14%	2.05%	2.12%	2.13%	2.07%
CaO	4.65%	4.57%	6.46%	8.40%	6.47%
Cr_2O_3	0.32%	0.39%	0.32%	0.43%	0.39%
F(1)	**0.61%**	**0.61%**	**0.64%**	**0.64%**	**0.61%**
Fe_2O_3	1.91%	1.81%	1.86%	1.90%	1.87%
K_2O	0.62%	0.58%	0.59%	0.60%	0.59%
La_2O_3	0.62%	0.65%	0.67%	0.61%	0.59%
Li_2O(1)	**5.00%**	**5.00%**	**5.00%**	**5.00%**	**5.00%**
MgO	0.19%	0.20%	0.18%	0.20%	0.20%
MnO	1.02%	1.03%	1.09%	1.10%	1.03%
Na_2O	9.18%	9.50%	10.88%	10.90%	9.45%
NiO	1.44%	1.40%	1.46%	1.50%	1.44%
P_2O_5	2.89%	3.28%	3.03%	3.35%	3.24%
PbO	0.12%	0.09%	0.09%	0.09%	0.09%
SO_3	0.98%	1.07%	1.13%	1.05%	0.98%
SiO_2	42.43%	42.26%	28.84%	39.77%	40.32%
TiO_2	0.05%	0.07%	0.06%	0.05%	0.06%
V_2O_5	—(2)	2.00%	—	1.94%	1.98%
ZrO_2	0.10%	0.10%	0.10%	3.57%	0.09%
TOTAL	100.0%	100.0%	100.0%	99.8%	100.0%

(1) B_2O_3, F, and Li_2O are not analyzed by XRF; target values (boldface) are used.
(2) — Empty data field (components not present in glass).

Table 2.19. Compositions of HLWS Glasses (wt%) Analyzed by XRF (Continued).

Oxide	**HLWS-11**	**HLWS-12**	**HLWS-13**	**HLWS-14**	**HLWS-15**
Al_2O_3	12.38%	12.30%	13.23%	23.28%	23.32%
B_2O_3(1)	**11.04%**	**11.04%**	**9.54%**	**19.04%**	**16.05%**
Bi_2O_3	2.06%	2.03%	2.22%	2.37%	2.71%
CaO	4.50%	4.45%	2.42%	2.51%	2.61%
Cr_2O_3	0.45%	0.39%	0.39%	0.32%	0.36%
F(1)	**0.61%**	**0.61%**	**0.68%**	**0.70%**	**0.75%**
Fe_2O_3	1.89%	1.84%	1.96%	2.03%	2.28%
K_2O	0.60%	0.62%	0.63%	0.62%	0.70%
La_2O_3	0.66%	0.84%	0.75%	0.75%	0.79%
Li_2O(1)	**5.00%**	**6.00%**	**5.00%**	**2.50%**	**3.50%**
MgO	0.18%	0.17%	0.20%	0.19%	0.16%
MnO	1.07%	1.02%	1.13%	1.22%	1.31%
Na_2O	9.54%	9.75%	11.15%	11.51%	11.37%
NiO	1.36%	1.39%	1.46%	1.52%	1.80%
P_2O_5	3.15%	3.16%	3.64%	3.70%	3.84%
PbO	0.09%	0.09%	0.10%	0.10%	0.12%
SO_3	1.00%	1.05%	1.09%	1.00%	1.08%
SiO_2	40.35%	41.12%	42.33%	26.46%	27.04%
TiO_2	0.06%	0.06%	0.06%	0.06%	0.07%
V_2O_5	3.91%	1.96%	1.90%	—(2)	—
ZrO_2	0.09%	0.09%	0.10%	0.10%	0.13%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%

(1) B_2O_3, F, and Li_2O are not analyzed by XRF; target values (boldface) are used.
(2) — Empty data field (components not present in glass).

Table 2.19. Compositions of HLWS Glasses (wt%) Analyzed by XRF (Continued).

Oxide	HLWS-16	HLWS-17	HLWS-18	HLWS-19	HLWS-20
Al_2O_3	23.39%	12.36%	12.54%	12.86%	21.85%
B_2O_3 (1)	**18.54%**	**9.05%**	**8.05%**	**9.54%**	**18.54%**
Bi_2O_3	2.31%	2.54%	2.71%	2.37%	2.44%
CaO	0.50%	3.57%	2.75%	0.49%	0.51%
Cr_2O_3	0.42%	0.46%	0.45%	0.60%	0.44%
F(1)	**0.64%**	**0.74%**	**0.78%**	**0.69%**	**0.70%**
Fe_2O_3	1.98%	2.37%	2.31%	2.01%	2.06%
K_2O	0.62%	0.67%	0.75%	0.68%	0.66%
La_2O_3	0.64%	1.05%	0.99%	0.80%	0.83%
Li_2O (1)	**4.00%**	**4.00%**	**4.00%**	**5.00%**	**4.00%**
MgO	0.21%	0.20%	0.29%	0.17%	0.22%
MnO	1.15%	1.27%	1.32%	1.10%	1.21%
Na_2O	9.89%	11.16%	12.27%	11.00%	11.06%
NiO	1.53%	1.74%	1.82%	1.58%	1.62%
P_2O_5	3.33%	3.93%	4.53%	3.83%	3.75%
PbO	0.11%	0.11%	0.12%	0.11%	0.13%
SO_3	1.04%	1.22%	1.73%	1.07%	1.08%
SiO_2	27.49%	41.37%	40.41%	41.99%	26.72%
TiO_2	0.05%	0.06%	0.06%	0.06%	0.06%
V_2O_5	2.04%	1.99%	2.01%	3.93%	1.99%
ZrO_2	0.11%	0.12%	0.12%	0.10%	0.11%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%

(1) B_2O_3, F, and Li_2O are not analyzed by XRF; target values (boldface) are used.
(2) — Empty data field (components not present in glass).

Table 2.20. Characterization Data of the HLWS Series of Glasses.

Property			HLWS-01	HLWS-02	HLWS-03	HLWS-04
Crystal Content after Heat Treatment(1) (vol%)		800°C	0.92 (Sp)	1.17 (Sp, PO)	1.00 (Sp)	5.77 (PO, Sp)
		850°C	0.68 (Sp)	0.59 (Sp)	0.70 (Sp)	4.89 (PO, Sp)
		900°C	0.19 (Sp)	0.28 (Sp)	0.35 (Sp)	4.65 (PO, Sp)
		950°C	0.03 (Sp)	0.05 (Sp)	0.10 (Sp)	2.69 (PO, Sp)
Viscosity (P)	**Experimental**	Temperature 1	—(2)	386.25 (957°C)	304.02 (955°C)	384.17 (958°C)
		Temperature 2	—	122.47 (1058°C)	100.50 (1056°C)	111.49 (1059°C)
		Temperature 3	—	49.28 (1160°C)	41.68 (1158°C)	40.50 (1161°C)
		Temperature 4	—	24.29 (1261°C)	20.68 (1259°C)	17.74 (1262°C)
	Fitted	1050°C	—	132.33	106.49	123.08
		1150°C	—	53.58	44.38	44.77
		1250°C	—	26.02	21.88	19.42
Electrical Conductivity (S/cm)	**Experimental**	Temperature 1	—	0.153 (962°C)	0.191 (962°C)	0.112 (964°C)
		Temperature 2	—	0.232 (1062°C)	0.286 (1062°C)	0.171 (1061°C)
		Temperature 3	—	0.324 (1159°C)	0.397 (1159°C)	0.245 (1157°C)
		Temperature 4	—	0.426 (1255°C)	0.514 (1255°C)	0.329 (1254°C)
	Fitted	1050°C	—	0.221	0.275	0.164
		1150°C	—	0.314	0.385	0.239
		1250°C	—	0.421	0.508	0.325
Normalized PCT (7 Day) (g/l)		B	—	—	—	—
		Li	—	—	—	—
		Na	—	—	—	—
Sulfate Solubility (wt% SO_3 in glass)		Target	1.22%	1.22%	1.22%	1.29%
		Over-Saturation	0.80%	0.70%	0.78%	1.29%
		Gas Bubbling	1.05%	0.86%	—	1.31%

(1) Sp = Spinel, PO = Phosphate (apatite).
(2) — Empty data field (not analyzed).

Table 2.20. Characterization Data of the HLWS Series of Glasses (Continued).

Property			HLWS-05	HLWS-06	HLWS-07	HLWS-08
Crystal Content after Heat Treatment(1) (vol%)		800°C	3.86 (PO, Sp)	3.86 (PO, Sp)	4.18 (PO, Sp)	10.8 (PO, Sp, Ha)
		850°C	4.50 (PO, Sp)	2.87 (PO, Sp)	3.28 (PO, Sp)	9.0 (PO, Sp, Ha)
		900°C	2.85 (PO, Sp)	1.67 (PO, Sp)	1.58 (PO, Sp)	8.2 (PO, Sp, Ha)
		950°C	1.15 (Sp)	0.08 (PO)	0.08 (PO)	2.3 (PO, Sp)
Viscosity (P)	**Experimental**	Temperature 1	—(2)	—	302.47 (957°C)	—
		Temperature 2	—	—	96.04 (1058°C)	—
		Temperature 3	—	—	38.78 (1160°C)	—
		Temperature 4	—	—	18.62 (1261°C)	—
	Fitted	1050°C	—	—	104.33	—
		1150°C	—	—	41.93	—
		1250°C	—	—	20.05	—
Electrical Conductivity (S/cm)	**Experimental**	Temperature 1	—	—	0.175 (965°C)	—
		Temperature 2	—	—	0.261 (1062°C)	—
		Temperature 3	—	—	0.365 (1158°C)	—
		Temperature 4	—	—	0.472 (1254°C)	—
	Fitted	1050°C	—	—	0.251	—
		1150°C	—	—	0.354	—
		1250°C	—	—	0.468	—
Normalized PCT (7 Day) (g/l)		B	1.740	—	—	—
		Li	1.877	—	—	—
		Na	1.131	—	—	—
Sulfate Solubility (wt% SO_3 in glass)		Target	1.29%	1.22%	1.22%	1.29%
		Over-Saturation	1.38%	1.19%	1.10%	1.29%
		Gas Bubbling	1.30%	—	—	1.29%

(1) Sp = Spinel, PO = Phosphate (apatite), Ha = Hauyne.
(2) — Empty data field (not analyzed).

Table 2.20. Characterization Data of the HLWS Series of Glasses (Continued).

Property			HLWS-09	HLWS-10	HLWS-11	HLWS-12
Crystal Content after Heat Treatment[1] (vol%)		800°C	5.13 (PO, Sp)	5.64 (PO, Sp)	4.37 (PO, Sp)	3.49 (PO, Sp)
		850°C	3.48 (PO, Sp)	3.28 (PO, Sp)	2.93 (PO, Sp)	1.34 (PO, Sp)
		900°C	1.24 (PO)	2.48 (PO, Sp)	1.87 (PO, Sp)	0.43 (PO, Sp)
		950°C	0.25 (PO)	0.72 (PO)	0.78 (PO, Sp)	0.10 (PO)
Viscosity (P)	Experimental	Temperature 1	156.53 (958°C)	194.32 (955°C)	—[2]	—
		Temperature 2	48.00 (1059°C)	62.57 (1056°C)	—	—
		Temperature 3	19.16 (1160°C)	25.89 (1158°C)	—	—
		Temperature 4	9.19 (1261°C)	12.69 (1258°C)	—	—
	Fitted	1050°C	52.69	66.69	—	—
		1150°C	20.79	27.42	—	—
		1250°C	9.89	13.40	—	—
Electrical Conductivity (S/cm)	Experimental	Temperature 1	0.181 (959°C)	0.148 (953°C)	—	—
		Temperature 2	0.279 (1058°C)	0.260 (1059°C)	—	—
		Temperature 3	0.406 (1156°C)	0.373 (1157°C)	—	—
		Temperature 4	0.595 (1251°C)	0.510 (1253°C)	—	—
	Fitted	1050°C	0.272	0.503	—	—
		1150°C	0.408	0.368	—	—
		1250°C	0.579	0.247	—	—
Normalized PCT (7 Day) (g/l)		B	0.653	—	0.348	—
		Li	0.741	—	0.505	—
		Na	0.692	—	0.309	—
Sulfate Solubility (wt% SO_3 in glass)		Target	1.29%	1.22%	1.22%	1.22%
		Over-Saturation	1.63%	1.55%	1.09%	1.33%
		Gas Bubbling	1.78%	1.74%	1.58%	1.78%

(1) Sp = Spinel, PO = Phosphate (apatite).
(2) — Empty data field (not analyzed).

Table 2.20. Characterization Data of the HLWS Series of Glasses (Continued).

Property			HLWS-13	HLWS-14	HLWS-15	HLWS-16
Crystal Content after Heat Treatment(1) (vol%)		800°C	3.37 (PO, Sp)	6.37 (PO, Sp)	5.52 (PO, Sp, No)	2.12 (Sp, PO)
		850°C	0.79 (PO, Sp)	5.26 (PO, Sp)	4.91 (PO, Sp)	1.70 (Sp, PO)
		900°C	0.21 (PO, Sp)	4.30 (PO, Sp)	3.31 (PO, Sp)	1.58 (Sp, PO)
		950°C	0.03 (PO, Sp)	2.38 (PO, Sp)	1.96 (Sp, PO)	1.28 (Sp, PO)
Viscosity (P)	Experimental	Temperature 1	—(2)	520.71 (959°C)	—	—
		Temperature 2	—	146.83 (1059°C)	—	—
		Temperature 3	—	52.77 (1160°C)	—	—
		Temperature 4	—	22.33 (1260°C)	—	—
	Fitted	1050°C	—	163.56	—	—
		1150°C	—	57.56	—	—
		1250°C	—	24.22	—	—
Electrical Conductivity (S/cm)	Experimental	Temperature 1	—	0.124 (954°C)	—	—
		Temperature 2	—	0.182 (1058°C)	—	—
		Temperature 3	—	0.258 (1156°C)	—	—
		Temperature 4	—	0.348 (1253°C)	—	—
	Fitted	1050°C	—	0.180	—	—
		1150°C	—	0.254	—	—
		1250°C	—	0.342	—	—
Normalized PCT (7 Day) (g/l)		B	—	1.576	—	—
		Li	—	1.580	—	—
		Na	—	1.000	—	—
Sulfate Solubility (wt% SO_3 in glass)		Target	1.38%	1.40%	1.50%	1.29%
		Over-Saturation	0.85%	1.18%	1.14%	1.33%
		Gas Bubbling	1.25%	1.25%	—	—

(1) Sp = Spinel, PO = Phosphate (apatite), No = Nosean.
(2) — Empty data field (not analyzed).

Table 2.20. Characterization Data of the HLWS Series of Glasses (Continued).

Property			**HLWS-17**	**HLWS-18**	**HLWS-19**	**HLWS-20**
Crystal Content after Heat Treatment[1] (vol%)		950°C	5.05 (PO, Sp)	4.42 (PO, Sp)	6.32 (PO, Sp)	2.79 (Sp, PO)
		900°C	3.56 (PO, Sp)	2.25 (PO, Sp)	0.50 (Sp)	1.80 (Sp, PO)
		850°C	2.79 (PO, Sp)	1.36 (PO, Sp)	0.29 (Sp)	1.50 (Sp, PO)
		800°C	0.62 (PO, Sp)	0.08 (Sp)	0.07 (Sp)	1.04 (Sp)
Viscosity (P)	**Experimental**	Temperature 1	—[2]	—	—	243.04 (957°C)
		Temperature 2	—	—	—	75.33 (1059°C)
		Temperature 3	—	—	—	30.92 (1162°C)
		Temperature 4	—	—	—	14.36 (1264°C)
	Fitted	1050°C	—	—	—	83.53
		1150°C	—	—	—	33.43
		1250°C	—	—	—	15.91
Electrical Conductivity (S/cm)	**Experimental**	Temperature 1	—	—	—	0.219 (968°C)
		Temperature 2	—	—	—	0.321 (1065°C)
		Temperature 3	—	—	—	0.448 (1160°C)
		Temperature 4	—	—	—	0.558 (1257°C)
	Fitted	1050°C	—	—	—	0.308
		1150°C	—	—	—	0.427
		1250°C	—	—	—	0.553
Normalized PCT (7 Day) (g/l)		B	—	—	—	—
		Li	—	—	—	—
		Na	—	—	—	—
Sulfate Solubility (wt% SO_3 in glass)		Target	1.47%	1.56%	1.38%	1.40%
		Over-Saturation	0.79%	0.74%	0.64%	1.26%
		Gas Bubbling	—	—	—	—

[1] Sp = Spinel, PO = Phosphate (apatite).
[2] — Empty data field (not analyzed).

Table 2.21. Regression Results[1], Estimated One-Percent Crystal Fraction Temperature ($T_{1\%}$) and the Major Crystalline Phase Near $T_{1\%}$ for the HLWS Series of Glasses.

Glass	Intercept	Slope	$T_{1\%}$ (°C)	Primary Crystalline Phase
HLWS-01	944.35	-152.41	791.94	Spinel
HLWS-02	942.91	-129.98	812.93	Spinel
HLWS-03	962.78	-163.32	799.46	Spinel
HLWS-04	1085.62	-46.81	1038.82	Calcium Phosphate
HLWS-05	1018.90	-50.67	968.23	Spinel
HLWS-06	958.56	-39.41	919.14	Calcium Phosphate
HLWS-07	956.27	-35.37	920.89	Calcium Phosphate
HLWS-08	997.75	-16.20	981.55	Calcium Phosphate
HLWS-09	948.36	-29.05	919.31	Calcium Phosphate
HLWS-10	969.19	-31.09	938.11	Calcium Phosphate
HLWS-11	979.55	-42.03	937.52	Calcium Phosphate
HLWS-12	928.12	-39.64	888.48	Calcium Phosphate
HLWS-13	941.36	-120.46	820.90	Calcium Phosphate
HLWS-14	1047.36	-37.65	1009.71	Calcium Phosphate
HLWS-15	1030.41	-39.59	990.81	Spinel
HLWS-16	1182.07	-128.51	1053.56	Spinel
HLWS-17	978.31	-34.38	943.93	Calcium Phosphate
HLWS-18	945.42	-34.73	910.69	Calcium Phosphate
HLWS-19	966.66	-232.52	734.14	Spinel
HLWS-20	1025.21	-84.21	940.94	Spinel

(1) Regression results are rounded to 2 decimal places.

Table 3.1. Gas Bubbling Experiments Test Matrix.

Reference	Origin	HLW Waste	Waste Limiting Element	Glass Name	Initial Sulfur Concentration from Target (wt% SO_3)	Measured Sulfur Solubility (wt% SO_3)
VSL-05R5800-1 [16], VSL-05R5710-1 [27]	WTP	C-106/AY-102 Actual Waste blended with AW-101 Cesium-Eluate	Iron	HLW04-09	0.19	0.65
VSL-11T2490-1 [28]	WTP	C-106/AY-102 Actual Waste blended with AW-101 Cesium-Eluate	Iron	HLW-NG-Fe2	0.22	0.83
VSL-11R2320-1 [22], VSL-11R2300-1 [29]	WTP	AZ-101 Envelope D Actual Waste	Iron	HLW98-95	0.12	0.66
VSL-05R5800-1 [16], VSL-03R3800-2 [30]	WTP	AZ-102	Iron	HLW98-80	0.041	0.66
VSL-07R1010-1 [20]	ORP	Al Limited	Aluminum	HLW-E-Al-27	0.20	1.09
VSL-08R1360-1 [31]	ORP	Al Limited	Aluminum	HWI-Al-19	0.20	1.25
VSL-07R1010-1 [20]	ORP	Al and Na Limited	Aluminum and Sodium	HLW-E-ANa-22	0.22	0.87
VSL-07R1010-1 [20]	ORP	Bi Limited	Bismuth	HLW-E-Bi-6	0.48	0.74

Table 3.2. Analyzed Composition of Melter Glasses Used in Gas Bubbling Experiments (wt%).

	KBL-G-11B	1Y2-G-111A	BLL-G-46B	BLM-G-152B	BLN-G-129A	G-12K-139A	1W2-G-58A	HBL-G-112A
Base Glass	HLW-NG-Fe2	HLW04-09	HLW-E-Bi-6	HLW-E-Al-27	HLW-E-ANa-22	HWI-Al-19	HLW98-80	HLW98-95
Measured Sulfur Solubility (wt% SO_3)	0.83	0.65	0.74	1.09	0.87	1.25	0.66	0.66
Al_2O_3	6.04	5.83	11.48	22.44	20.74	23.64	5.99	8.51
As_2O_3	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
B_2O_3	14.45	10.17	11.29	15.2	18.29	19.13	12.52	10.96
BaO	0.12	0.07	0.03	0.33	0.07	0.07	0.01	<0.01
Bi_2O_3	0.01	<0.01	6.67	1.21	1.17	1.15	<0.01	0.1
CaO	0.6	0.52	0.87	5.61	1.1	5.45	0.35	0.8
CdO	0.03	<0.01	<0.01	<0.01	<0.01	0.03	0.12	0.62
Ce_2O_3	0.1	0.07	<0.01	<0.01	<0.01	<0.01	<0.01	0.27
Cl	<0.01	0.01	0.05	<0.01	<0.01	<0.01	<0.01	<0.01
Cr_2O_3	0.23	0.22	0.51	0.49	0.78	0.53	0.02	0.2
Cs_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.06	0.08
CuO	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NA
F	<0.01	<0.01	0.49	0.43	0.18	0.37	<0.01	<0.01
Fe_2O_3	17	13.27	7.38	5.79	3.12	6.07	11.35	11.2
K_2O	0.32	0.13	0.54	0.45	0.7	0.19	0.16	0.44
La_2O_3	0.11	0.06	<0.01	<0.01	<0.01	<0.01	0.37	0.09
Li_2O	1.44	2.7	0.18	3.57	3.58	3.56	3.26	3.72
MgO	0.3	0.33	0.5	0.39	0.26	0.31	0.09	0.14
MnO	2.48	3.09	0.15	0.04	0.05	0.04	0.35	0.28
Na_2O	14.04	12.48	15.23	9.98	12.82	9.84	12.71	11.42
Nd_2O_3	<0.01	0.03	0.05	0.01	0.01	<0.01	0.17	0.15
NiO	0.5	0.35	1.67	0.3	0.16	0.33	0.39	0.48
P_2O_5	0.64	0.53	5.06	1.13	1.99	1.16	0.04	0.52
PbO	0.49	0.07	0.3	0.35	0.1	0.34	0.05	0.02
RuO_2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02
SO_3	0.4	0.16	0.43	0.16	0.16	0.14	0.08	0.15
Sb_2O_3	<0.01	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SiO_2	39.24	46.76	36.27	31.54	34.17	26.99	48.12	44.13
SnO_2	0.09	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	0.15
SrO	0.17	0.29	0.03	<0.01	<0.01	<0.01	<0.01	<0.01
TiO_2	0.08	0.09	0.19	0.05	0.16	0.04	0.07	0.04
ZnO	0.09	1.11	0.2	0.09	0.17	0.11	1.64	1.67
ZrO_2	1.03	1.17	0.42	0.47	0.2	0.5	2.09	3.82
TOTAL	100	100	100	100	100	100	100	100

Table 3.3. Target Compositions of HLW Glasses Measured for Sulfate Solubility [18].

Oxide	HLW98-77	HLW98-86	HLW98-96[b]	HLW02-15	HLW02-22
Measured Sulfate Solubility	0.58%	0.73%	0.54%	0.83%	0.60%
Ag_2O	0.02%	0.15%	0.03%	0.20%	0.02%
Al_2O_3	5.20%	5.29%	3.36%	8.50%	8.50%
As_2O_3	—[a]	0.19%	—	0.23%	0.02%
B_2O_3	11.91%	9.39%	10.10%	14.00%	14.00%
BaO	—	—	—	0.30%	0.03%
Bi_2O_3	—	—	—	0.01%	0.01%
CaO	0.28%	0.30%	0.45%	0.50%	0.50%
CdO	0.06%	—	—	0.05%	0.05%
Ce_2O_3	—	—	—	0.05%	0.05%
Cl	—	0.11%	—	0.20%	0.20%
CoO	—	—	—	0.01%	0.01%
Cr_2O_3	—	0.08%	0.06%	0.20%	0.02%
Cs_2O	—	—	—	0.01%	0.01%
CuO	0.03%	0.04%	0.03%	0.10%	0.01%
F	0.04%	—	0.11%	0.05%	0.05%
Fe_2O_3	12.22%	12.56%	8.95%	14.00%	9.50%
K_2O	0.03%	—	—	0.06%	0.06%
La_2O_3	0.41%	0.24%	0.15%	0.30%	0.30%
Li_2O	3.53%	3.01%	3.09%	2.00%	6.00%
MgO	0.11%	1.17%	—	0.12%	0.12%
MnO	0.17%	3.99%	1.42%	4.69%	0.00%
Na_2O	11.66%	11.84%	10.74%	12.54%	4.00%
Nd_2O_3	0.31%	0.15%	0.10%	—	—
NiO	0.61%	0.17%	0.44%	0.10%	0.10%
P_2O_5	—	0.09%	0.04%	0.50%	0.50%
PbO	0.03%	0.14%	0.11%	0.40%	0.04%
PdO	—	—	—	0.12%	0.12%
Rh_2O_3	—	—	—	0.05%	0.05%
RuO_2	—	—	—	0.08%	0.08%
SO_3	0.08%	—	—	0.10%	0.10%
Sb_2O_3	—	0.26%	—	0.02%	0.20%
SeO_2	—	0.37%	—	0.20%	0.20%
SiO_2	47.45%	47.07%	43.32%	37.99%	53.00%
SrO	0.03%	0.92%	—	0.00%[c]	0.08%
TeO_2	—	—	—	0.01%	0.01%
ThO_2	—	—	4.05%	0.00%	0.00%
TiO_2	—	0.14%	0.02%	0.03%	0.03%
Tl_2O	—	—	—	0.19%	0.02%
UO_3	—	—	2.57%	0.00%	0.00%
V_2O_5	—	—	—	0.10%	0.01%
ZnO	2.02%	2.07%	2.02%	2.00%	2.00%
ZrO_2	3.81%	0.26%	8.84%	0.00%	0.00%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%

[a] — indicates empty data field.
[b] Composition is different than that given in Reference [8] because of revised oxide forms (e.g., UO_3 used instead of UO_2).
[c] A value of 0.00% indicates that the oxide is part of the matrix design but the oxide is absent from the selected glass.

Table 3.3. Target Compositions of HLW Glasses Measured for Sulfate Solubility [18] (Continued).

Oxide	HLW02-24	HLW02-26	HLW02-43	HLW02-46	HLW02-50
Measured Sulfur Solubility	0.58%	0.61%	0.82%	0.53%	0.59%
Ag_2O	0.15%	0.20%	0.04%	0.04%	0.04%
Al_2O_3	8.50%	4.00%	6.50%	5.50%	6.00%
As_2O_3	0.18%	0.23%	0.05%	0.05%	0.05%
B_2O_3	5.00%	5.00%	13.00%	9.15%	13.00%
BaO	0.23%	0.30%	0.06%	0.06%	0.06%
Bi_2O_3	0.01%	0.01%	0.01%	0.01%	0.01%
CaO	0.50%	0.50%	0.50%	0.50%	0.50%
CdO	0.05%	1.50%	1.00%	0.50%	0.50%
Ce_2O_3	0.05%	0.05%	0.05%	0.05%	0.05%
Cl	0.20%	0.20%	0.20%	0.20%	0.20%
CoO	0.01%	0.01%	0.01%	0.01%	0.01%
Cr_2O_3	0.15%	0.20%	0.04%	0.04%	0.04%
Cs_2O	0.01%	0.01%	0.01%	0.01%	0.01%
CuO	0.08%	0.10%	0.02%	0.02%	0.02%
F	0.05%	0.05%	0.05%	0.05%	0.05%
Fe_2O_3	8.00%	12.50%	10.00%	10.00%	12.00%
K_2O	0.06%	0.06%	0.06%	0.06%	0.06%
La_2O_3	0.30%	0.30%	0.30%	0.30%	0.30%
Li_2O	2.00%	2.00%	2.50%	3.70%	2.50%
MgO	0.12%	0.12%	0.12%	0.12%	0.12%
MnO	5.00%	4.96%	3.50%	3.50%	1.50%
Na_2O	12.20%	15.00%	12.45%	9.00%	9.82%
NiO	0.10%	0.10%	0.30%	0.80%	0.30%
P_2O_5	0.50%	0.50%	0.50%	0.50%	0.50%
PbO	0.31%	0.40%	0.08%	0.08%	0.08%
PdO	0.12%	0.12%	0.12%	0.12%	0.12%
Rh_2O_3	0.05%	0.05%	0.05%	0.05%	0.05%
RuO_2	0.08%	0.08%	0.08%	0.08%	0.08%
SO_3	0.10%	0.10%	0.10%	0.10%	0.10%
Sb_2O_3	0.02%	0.02%	0.15%	0.05%	0.15%
SeO_2	0.20%	0.02%	0.05%	0.15%	0.05%
SiO_2	47.05%	37.99%	41.00%	49.00%	43.53%
SrO	5.00%	5.00%	3.50%	1.50%	1.50%
TeO_2	0.01%	0.01%	0.01%	0.01%	0.01%
ThO_2	0.00%(b)	0.00%	0.00%	0.00%	0.00%
TiO_2	0.03%	0.03%	0.03%	0.03%	0.03%
Tl_2O	0.02%	0.19%	0.05%	0.14%	0.14%
UO_3	0.00%	0.00%	0.00%	0.00%	0.00%
V_2O_5	0.08%	0.10%	0.02%	0.02%	0.02%
ZnO	2.00%	2.00%	2.00%	2.00%	2.00%
ZrO_2	1.50%	6.00%	1.50%	2.50%	4.50%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%

(a) — indicates empty data field.

(b) A value of 0.00% indicates that the oxide is part of the matrix design but the oxide is absent from the selected glass.

Table 3.3. Target Compositions of HLW Glasses Measured for Sulfate Solubility [18] (Continued).

Oxide	HLW03-01	HLW03-03	HLW04-07S1	HLW06-16	HLW06-22
Measured Sulfur Solubility	1.12%	0.63%	0.62%	0.84%	1.60%
Ag_2O	0.20%	0.02%	—	0.10%	0.10%
Al_2O_3	8.34%	1.95%	4.90%	10.00%	13.00%
As_2O_3	0.23%	0.02%	—	—	—
B_2O_3	13.73%	4.88%	10.29%	6.50%	15.00%
BaO	0.30%	0.03%	0.07%	0.10%	0.00%
Bi_2O_3	0.01%	0.01%	—	0.30%	0.30%
CaO	0.50%	0.50%	0.46%	0.32%	0.00%
CdO	0.05%	1.60%	—	0.24%	1.65%
Ce_2O_3	0.05%	0.05%	0.10%	—	—
Cl	0.20%	0.20%	—	0.20%	0.20%
CoO	0.01%	0.01%	—	—	—
Cr_2O_3	0.02%	0.49%	0.22%	0.25%	0.60%
Cs_2O	0.01%	0.01%	0.00%	—	—
CuO	0.10%	0.01%	—	—	—
F	0.05%	0.05%	—	0.44%	0.44%
Fe_2O_3	13.73%	13.68%	14.05%	7.00%	1.40%
K_2O	0.06%	0.06%	—	0.52%	0.00%
La_2O_3	0.30%	0.30%	0.08%	0.18%	1.23%
Li_2O	5.88%	2.68%	2.65%	3.00%	6.01%
MgO	0.12%	0.12%	0.15%	0.37%	0.00%
MnO	6.08%	6.84%	2.83%	1.75%	0.00%
Na_2O	3.92%	10.76%	12.57%	20.00%	6.84%
Nd_2O_3	—[a]	—	—	0.33%	0.80%
NiO	0.10%	0.98%	0.41%	1.00%	0.00%
P_2O_5	0.50%	0.50%	0.56%	0.50%	0.50%
PbO	0.40%	0.04%	0.54%	0.29%	0.00%
PdO	0.12%	0.12%	—	0.12%	0.12%
Rh_2O_3	0.05%	0.05%	—	0.05%	0.05%
RuO_2	0.08%	0.08%	—	0.13%	0.13%
SO_3	0.10%	0.10%	—	0.04%	0.28%
Sb_2O_3	0.02%	0.02%	—	—	—
SeO_2	0.20%	0.20%	—	—	—
SiO_2	35.30%	35.17%	47.84%	35.00%	34.56%
SnO_2	—	—	0.06%	—	—
SrO	0.00%[b]	9.77%	0.17%	1.47%	10.29%
TeO_2	0.01%	0.01%	—	—	—
ThO_2	2.76%	0.00%	—	1.50%	0.00%
TiO_2	0.03%	0.03%	—	0.32%	0.00%
Tl_2O	0.31%	0.31%	—	—	—
UO_3	0.00%	0.00%	—	4.00%	6.50%
V_2O_5	0.10%	0.01%	—	—	—
ZnO	3.06%	1.95%	1.03%	2.50%	0.00%
ZrO_2	2.98%	6.40%	0.99%	1.50%	0.00%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%

[a] — indicates empty data field.
[b] A value of 0.00% indicates that the oxide is part of the matrix design but the oxide is absent from the selected glass.

Table 3.3. Target Compositions of HLW Glasses Measured for Sulfate Solubility [18] (Continued).

Oxide	HLW06-24	HLW06-27	HLW06-29	HLW06-32	HLW-ALG-03
Measured Sulfur Solubility	0.65%	0.64%	0.72%	0.85%	0.87%
Ag_2O	0.10%	0.10%	0.10%	0.10%	0.05%
Al_2O_3	13.00%	1.88%	1.88%	1.88%	1.93%
As_2O_3	—(a)	—	—	—	—
B_2O_3	4.30%	9.82%	4.30%	15.00%	8.62%
BaO	0.30%	0.00%	0.30%	0.00%	0.04%
Bi_2O_3	0.30%	0.30%	0.30%	0.30%	—
CaO	1.00%	0.00%	1.00%	0.00%	0.34%
CdO	1.65%	0.00%	0.00%	0.00%	—
Ce_2O_3	—	—	—	—	0.05%
Cl	0.20%	0.20%	0.20%	0.20%	—
Cr_2O_3	0.00%(b)	0.00%	0.00%	0.60%	0.50%
F	0.44%	0.44%	0.44%	0.44%	0.03%
Fe_2O_3	1.40%	1.40%	15.00%	15.00%	12.65%
K_2O	1.64%	0.00%	1.64%	0.00%	0.13%
La_2O_3	1.23%	0.00%	0.00%	0.00%	0.10%
Li_2O	0.00%	6.01%	6.01%	0.00%	3.06%
MgO	1.17%	0.00%	1.17%	0.00%	0.10%
MnO	0.00%	0.00%	0.00%	8.00%	2.10%
Na_2O	16.25%	3.70%	3.70%	20.00%	18.97%
Nd_2O_3	0.80%	0.25%	0.25%	0.25%	0.09%
NiO	0.00%	0.00%	0.00%	0.00%	1.00%
P_2O_5	0.50%	0.50%	0.50%	0.50%	0.10%
PbO	0.91%	0.00%	0.91%	0.00%	0.21%
PdO	0.12%	0.12%	0.12%	0.12%	—
Rh_2O_3	0.05%	0.05%	0.05%	0.05%	—
RuO_2	0.13%	0.13%	0.13%	0.13%	0.03%
SO_3	0.28%	0.00%	0.00%	0.00%	0.05%
SiO_2	33.00%	53.10%	43.56%	37.43%	44.37%
SrO	10.29%	0.00%	0.00%	0.00%	—
ThO_2	5.94%	0.00%	5.94%	0.00%	—
TiO_2	1.00%	0.00%	1.00%	0.00%	0.04%
UO_3	0.00%	6.50%	0.00%	0.00%	—
ZnO	4.00%	4.00%	0.00%	0.00%	0.03%
ZrO_2	0.00%	11.50%	11.50%	0.00%	5.43%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%

(a) — indicates empty data field.

(b) A value of 0.00% indicates that the oxide is part of the matrix design but the oxide is absent from the selected glass.

Table 4.1. Summary of DM10 Melter Tests.

Test		**1 A**	**1 B**	**1 C**
	Feeding Interval	3/26/12 13:00 – 3/27/12 8:05	3/27/12 11:00 – 3/28/12 7:00	3/28/12 10:45 – 3/29/12 10:15
	Total	19.1 hr	20.0 hr	23.5 hr
Feed	Glass Formulation	HWI-Al-19	HWI-Al-19	HWI-Al-19
	Target SO_3 Conc. (wt%)	0.4	0.6	0.8
	Waste Loading (%)	45	45	45
	Processed (kg)	61.485	59.035	68.440
	Processing rate (kg/hr)	3.2	3.0	2.9
Glass	Produced from feed (kg)	23.98	23.02	26.69
	Discharged (kg)	21.28	21.72	26.14
	Test Average Production Rate (kg/m^2/day)*	1436	1316	1298
	Measured SO_3 Conc. (wt%)	0.21	0.38	0.53
	Secondary sulfate phase on glass pool samples	0 of 3	0 of 3	0 of 3
Test Average Glass Temperature (°C)	2" from floor	1158	1156	1157
	4" from floor	1147	1147	1143
Test Average Plenum Temperature (°C)	Exposed	574	550	541
	Thermowell	587	564	564
Test Average Electrode Temperature (°C)		954	944	947
Test Average Discharge Chamber Temperature (°C)		1064	1046	1045
Test Average Film Cooler Exhaust Outlet Temperature (°C)		303	296	295
Test Average Melter Pressure (inches water)		-1.0	-0.9	-1.0
Test Average Melt Pool Bubbling (lpm)		0.7	0.8	0.6
Test Average Electrical Properties	Voltage (volts)	32.1	32.4	32.1
	Current (amps)	167	162	168
	Power (kW)	5.4	5.3	5.4
	Glass Pool Resistance (ohms)	0.192	0.200	0.192

* - Calculated from total feed processed
NA – Not Applicable

Table 4.1. Summary of DM10 Melter Tests (Continued).

Test		1 D	1 E	1 F
	Feeding Interval	3/29/12 11:15 – 3/30/12 9:45	3/30/12 10:40 – 3/30/12 20:40	4/10/12 10:18 – 4/11/12 5:36
	Total	22.5 hr	10.0 hr	19.3 hr
Feed	Glass Formulation	HWI-Al-19	HWI-Al-19	HWI-Al-19
	Target SO_3 Conc. (wt%)	1.0	1.3	1.6
	Waste Loading (%)	45	45	45
	Processed (kg)	66.762	31.470	59.495
	Processing rate (kg/hr)	3.0	3.1	3.1
Glass	Produced from feed (kg)	26.04	12.27	23.2
	Discharged (kg)	25.40	8.92	20.5
	Test Average Production Rate (kg/m^2/day)*	1323	1403	1374
	Measured SO_3 Conc. (wt%)	0.66	0.82	0.99
	Secondary sulfate phase on glass pool samples	0 of 3	0 of 3	3 of 5
Test Average Glass Temperature (°C)	2" from floor	1157	1156	1158
	4" from floor	1139	1135	1149
Test Average Plenum Temperature (°C)	Exposed	534	542	493
	Thermowell	558	570	553
Test Average Electrode Temperature (°C)		948	952	981
Test Average Discharge Chamber Temperature (°C)		1048	1048	1059
Test Average Film Cooler Exhaust Outlet Temperature (°C)		291	296	286
Test Average Melter Pressure (inches water)		-1.0	-1.0	-0.9
Test Average Melt Pool Bubbling (lpm)		0.5	0.4	0.9
Test Average Electrical Properties	Voltage (volts)	31.7	31.3	32.2
	Current (amps)	173	171	153
	Power (kW)	5.5	5.4	5.0
	Glass Pool Resistance (ohms)	0.184	0.184	0.212

* - Calculated from total feed processed
NA – Not Applicable

Table 4.1. Summary of DM10 Melter Tests (Continued).

Test		1 G	1 H	2 A
	Feeding Interval	4/11/12 10:20 – 4/12/12 7:14	4/12/12 14:45 – 4/13/12 12:40	4/16/12 10:00 – 4/17/12 7:00
	Total	20.9 hr	21.9 hr	21.0 hr
Feed	Glass Formulation	HWI-Al-19	HWI-Al-19	HLW-NG-Fe2
	Target SO_3 Conc. (wt%)	1.4	1.3	0.7
	Waste Loading (%)	45	45	42.3
	Processed (kg)	61.540	66.175	64.795
	Processing rate (kg/hr)	2.9	3.0	3.1
Glass	Produced from feed (kg)	24.00	25.81	24.62
	Discharged (kg)	21.14	22.34	23.01
	Test Average Production Rate (kg/m^2/day)*	1312	1346	1340
	Measured SO_3 Conc. (wt%)	0.91	0.76	0.45
	Secondary sulfate phase on glass pool samples	4 of 5	1 of 3	3 of 4
Test Average Glass Temperature (°C)	2" from floor	1158	1157	1157
	4" from floor	1147	1148	1153
Test Average Plenum Temperature (°C)	Exposed	519	530	507
	Thermowell	552	547	564
Test Average Electrode Temperature (°C)		990	979	973
Test Average Discharge Chamber Temperature (°C)		1080	1057	1063
Test Average Film Cooler Exhaust Outlet Temperature (°C)		283	285	300
Test Average Melter Pressure (inches water)		-1.1	-1.0	-1.1
Test Average Melt Pool Bubbling (lpm)		0.6	1.2	2.6
Test Average Electrical Properties	Voltage (volts)	31.9	33.3	33.6
	Current (amps)	165	159	152.0
	Power (kW)	5.3	5.3	5.1
	Glass Pool Resistance (ohms)	0.193	0.210	0.221

* - Calculated from total feed processed
NA – Not Applicable

Table 4.1. Summary of DM10 Melter Tests (Continued).

Test		**2 B**	**2 C**	**2 D**
	Feeding Interval	4/17/12 11:00 – 4/18/12 7:45	4/18/12 13:00 – 4/19/12 9:00	4/19/12 9:50 – 4/19/12 18:15
	Total	20.7 hr	20.0 hr	8.4 hr
Feed	Glass Formulation	HLW-NG-Fe2	HLW-NG-Fe2	HLW-NG-Fe2
	Target SO_3 Conc. (wt%)	0.6	0.5	0.4
	Waste Loading (%)	42.3	42.3	42.3
	Processed (kg)	62.515	61.955	27.765
	Processing rate (kg/hr)	3.0	3.1	3.3
Glass	Produced from feed (kg)	23.76	23.54	10.55
	Discharged (kg)	21.12	22.02	8.70
	Test Average Production Rate (kg/m^2/day)*	1308	1345	1433
	Measured SO_3 Conc. (wt%)	0.36	0.34	0.34
	Secondary sulfate phase on glass pool samples	2 of 3	0 of 3	1 of 3
Test Average Glass Temperature (°C)	2” from floor	1154	1154	1154
	4” from floor	1143	1147	1146
Test Average Plenum Temperature (°C)	Exposed	519	505	507
	Thermowell	565	556	557
Test Average Electrode Temperature (°C)		997	988	992
Test Average Discharge Chamber Temperature (°C)		1061	1060	1057
Test Average Film Cooler Exhaust Outlet Temperature (°C)		296	292	294
Test Average Melter Pressure (inches water)		-1.1	-1.1	-0.9
Test Average Melt Pool Bubbling (lpm)		1.2	1.5	1.5
Test Average Electrical Properties	Voltage (volts)	32.3	32.5	33.0
	Current (amps)	166.5	160.2	164.7
	Power (kW)	5.4	5.2	5.5
	Glass Pool Resistance (ohms)	0.194	0.203	0.200

* - Calculated from total feed processed
NA – Not Applicable

Table 4.1. Summary of DM10 Melter Tests (Continued).

Test		**3 A**	**3 B**	**3 C**
	Feeding Interval	6/25/12 10:30 – 6/27/12 8:30	6/27/12 10:00 – 6/28/12 8:30	6/28/12 10:00 – 6/29/12 8:40
	Interruptions	24.4 hr	0	0
	Total	46.0 hr	22.5 hr	22.7 hr
Feed	Glass Formulation	HLWS-09	HLWS-09	HLWS-09
	Target SO_3 Conc. (wt%)	1.20	1.42	1.63
	Waste Loading (%)	28	33	38
	Processed (kg)	61.510	67.955	72.850
	Processing rate (kg/hr)	2.8	3.0	3.2
Glass	Produced from feed (kg)	24.73	26.73	27.25
	Discharged (kg)	22.74	23.78	25.99
	Test Average Production Rate (kg/m^2/day)*	1306	1339	1374
	Measured SO_3 Conc. (wt%)	0.87	1.04	1.17
	Secondary sulfate phase on glass pool samples	0 of 3	0 of 3	0 of 3
Test Average Glass Temperature (°C)	2" from floor	1147	1134	1127
	4" from floor	1142	1128	1121
Test Average Plenum Temperature (°C)	Exposed	467	422	448
	Thermowell	619	520	525
Test Average Electrode Temperature (°C)		1048	1036	1048
Test Average Discharge Chamber Temperature (°C)		1041	1035	1036
Test Average Film Cooler Exhaust Outlet Temperature (°C)		265	257	256
Test Average Melter Pressure (inches water)		-1.1	-0.9	-0.9
Test Average Melt Pool Bubbling (lpm)		0.4	1.0	1.0
Test Average Electrical Properties	Voltage (volts)	27.5	26.4	26.5
	Current (amps)	190	210	217
	Power (kW)	5.2	5.5	5.8
	Glass Pool Resistance (ohms)	0.145	0.126	0.122

* - Calculated from total feed processed
NA – Not Applicable

Table 4.1. Summary of DM10 Melter Tests (Continued).

Test		**3A-2**	**3 D**	**3 E**
	Feeding Interval	6/29/12 12:21 – 6/29/12 17:40	7/10/12 15:00 – 7/11/12 8:32	7/11/12 10:15 – 7/12/12 6:40
		0	0	1.25 hr
	Total	5.3 hr	17.5 hr	20.4 hr
Feed	Glass Formulation	HLWS-09	HLWS-09	HLWS-09
	Target SO_3 Conc. (wt%)	1.20	1.71	1.91
	Waste Loading (%)	28	28	28
	Processed (kg)	21.480	47.725	52.490
	Processing rate (kg/hr)	4.0	2.8	2.7
Glass	Produced from feed (kg)	8.63	19.99	21.1
	Discharged (kg)	8.32	18.36	21.07
	Test Average Production Rate (kg/m^2/day)*	1856	1303	1258
	Measured SO_3 Conc. (wt%)	1.07	1.30	1.58
	Secondary sulfate phase on glass pool samples	0 of 3	0 of 3	0 of 3
Test Average Glass Temperature (°C)	2" from floor	1141	1156	1156
	4" from floor	1135	1152	1150
Test Average Plenum Temperature (°C)	Exposed	485	518	497
	Thermowell	538	543	534
Test Average Electrode Temperature (°C)		1048	1076	1075
Test Average Discharge Chamber Temperature (°C)		1039	1035	1056
Test Average Film Cooler Exhaust Outlet Temperature (°C)		258	265	261
Test Average Melter Pressure (inches water)		-0.8	-0.9	-0.9
Test Average Melt Pool Bubbling (lpm)		1.3	2.2	1.7
Test Average Electrical Properties	Voltage (volts)	28.0	28.5	28.9
	Current (amps)	216	173	172
	Power (kW)	6.1	5.0	5.0
	Glass Pool Resistance (ohms)	0.129	0.165	0.169

* - Calculated from total feed processed
NA – Not Applicable

Table 5.1. Characteristics of Feed Samples.

Base Glass	Source	Date	Name	% Water	pH	Density (g/ml)	Glass Yield			
							(g/l)	Measured (kg/kg)	Target (kg/kg)	%Dev.
HWI-Al-19	Drum	3/13/12	10V-F-94B	46.87	8.30	1.48	670	0.453	NC	NC
	Residual Feed	3/30/12	10W-F-17A	54.86	9.04	1.38	538	0.390	0.358	8.88
	Residual Feed	4/13/12	10W-F-66A	54.40	9.00	1.45	563	0.388	0.358	5.18
HLW-NG-Fe2	Drum	3/13/12	10V-F-94A	57.54	11.33	1.39	528	0.380	0.369	2.95
	Residual Feed	4/4/12	10W-F-20A	56.61	11.23	1.39	529	0.381	0.369	3.20
	Residual Feed	4/19/12	10W-F-127A	57.08	11.32	1.41	528	0.375	0.369	1.49
HLWS-09	Residual Feed	6/21/12	10X-F-112A	38.41	9.90	1.47	592	0.402	0.404	0.5
	Residual Feed	6/29/12	10Y-F-24A	55.55	10.65	1.40	523	0.374	0.364	2.74

NC – Not calculated

Table 5.2. XRF Analyzed Compositions for the Vitrified Melter Feed Samples; HWI-Al-19.

Constituent	Target	10V-F-94B	10W-F-17A	10W-F-66A	Average	% Dev.
Al_2O_3	23.97	23.91	24.35	25.83	24.69	3.01
B_2O_3	19.19	19.13*	18.89*	18.51*	18.84	-1.83
BaO	0.05	0.08	0.08	0.08	0.08	NC
Bi_2O_3	1.14	1.24	1.28	1.14	1.22	6.81
CaO	5.58	5.50	5.48	5.06	5.35	-4.18
CdO	0.02	0.05	0.04	0.04	0.04	NC
Cr2O3	0.52	0.59	0.55	0.48	0.54	NC
F	0.67	$0.67^{\$}$	$0.67^{\$}$	$0.67^{\$}$	0.67	NC
Fe_2O_3	5.90	6.46	6.56	5.82	6.28	6.44
K_2O	0.14	0.06	0.05	0.12	0.08	NC
Li_2O	3.57	3.49*	3.51*	3.44*	3.48	-2.45
MgO	0.12	0.20	0.20	0.18	0.19	NC
MnO	§	0.02	0.03	0.02	0.02	NC
Na_2O	9.58	10.58	10.38	10.52	10.49	9.53
NiO	0.40	0.43	0.43	0.39	0.42	NC
P_2O_5	1.05	1.19	1.20	1.18	1.19	13.41
PbO	0.41	0.40	0.41	0.37	0.39	NC
SiO_2	27.00	25.19	24.75	24.88	24.94	-7.65
SO_3	0.4 – 1.6	0.16	0.53	0.71	NC	NC
SrO	§	<0.01	0.01	<0.01	<0.01	NC
TiO_2	0.01	0.12	0.11	0.09	0.11	NC
ZnO	0.08	0.09	0.10	0.08	0.09	NC
ZrO_2	0.39	0.43	0.42	0.38	0.41	NC
Sum	100.00	100.00	100.00	100.00	100.00	NC

§ - Not a target constituent
* - DCP-AES measured values
$^{\$}$ - Target value; not analyzed by XRF
NC – Not calculated

Table 5.3. XRF Analyzed Compositions for the Vitrified Melter Feed Samples; HLW-NG-Fe2.

Constituent	Target	As Received Feed	Residual Feed from Tests			
		10V-F-94A	10W-F-20A	10W-F-127A	Average	% Dev.
Al_2O_3	5.58	6.30	6.05	6.22	6.14	9.98
B_2O_3	13.81	11.61*	13.51*	13.88*	13.70	-.082
BaO	0.08	0.14	0.12	0.14	0.13	NC
CaO	0.52	0.66	0.61	0.57	0.59	NC
CdO	§	0.03	0.02	0.02	0.02	NC
Ce_2O_3	0.11	0.11	0.10	0.12	0.11	NC
Cr_2O_3	0.25	0.25	0.22	0.19	0.21	NC
Fe_2O_3	16.01	15.33	15.20	14.39	14.79	-7.59
K_2O	§	0.35	0.37	0.37	0.37	NC
La_2O_3	0.09	0.12	0.08	0.09	0.09	NC
Li_2O	1.55	1.54*	1.51*	1.53*	1.52	-2.02
MgO	0.17	0.33	0.32	0.32	0.32	NC
MnO	3.22	2.97	2.60	2.34	2.47	-23.27
Na_2O	14.16	12.61	13.50	14.36	13.93	-1.63
NiO	0.47	0.51	0.47	0.43	0.45	NC
P_2O_5	0.64	0.63	0.64	0.59	0.61	NC
PbO	0.62	0.55	0.50	0.46	0.48	NC
SiO_2	41.05	44.34	42.32	42.38	42.35	3.16
SnO_2	0.07	0.10	0.09	0.08	0.08	NC
SO_3	0.22-0.7	0.28	0.44	0.30	0.37	NC
SrO	0.20	0.19	0.17	0.15	0.16	NC
TiO_2	§	0.09	0.08	0.07	0.08	NC
ZnO	0.03	0.08	0.08	0.07	0.07	NC
ZrO_2	1.12	1.07	0.98	0.90	0.94	16.07
Sum	100.00	100.00	100.00	100.00	100.00	NC

§ - Not a target constituent
* - DCP-AES measured values
NC – Not calculated

Table 5.4. XRF Analyzed Compositions for the Vitrified Melter Feed Samples; HLWS-09.

Constituent	Target	1OX-F-112A		Target	1OY-F-24A	
		XRF	% Dev.		XRF	% Dev.
Al_2O_3	8.03	7.58	-5.73	8.31	8.38	0.74
B_2O_3	8.54	8.52^*	-0.24	7.67	8.08^*	5.40
Bi_2O_3	1.95	2.20	12.41	2.48	2.72	9.69
CaO	8.45	8.55	0.95	7.74	7.92	2.32
Cl	§	0.01	NC	§	0.01	NC
Cr_2O_3	0.32	0.39	NC	0.40	0.47	NC
F	0.64	$0.64^{\$}$	NC	0.82	$0.82^{\$}$	NC
Fe_2O_3	1.83	2.05	11.46	2.32	2.52	8.65
K_2O	0.68	0.69	NC	0.86	0.84	NC
La_2O_3	0.55	0.61	NC	0.70	0.90	NC
Li_2O	5.00	5.10^*	2.00	4.48	4.30^*	-4.00
MgO	0.20	0.24	NC	0.26	0.28	NC
MnO	1.07	1.02	-4.75	1.36	0.52	-61.8
Na_2O	10.11	10.06	-0.67	12.82	12.72	-0.81
NiO	1.32	1.53	15.95	1.67	1.88	12.53
P_2O_5	3.08	3.48	13.07	3.90	4.09	4.95
PbO	0.09	0.11	NC	0.12	0.11	NC
SiO_2	41.29	41.20	-0.22	37.47	39.78	6.16
SO_3	1.20	0.55	NC	1.52	1.19	NC
SrO	§	<0.01	NC	§	0.01	NC
TiO_2	0.04	0.17	NC	0.05	0.15	NC
V_2O_5	2.00	1.91	-4.45	1.79	1.72	-3.74
ZnO	§	0.01	NC	§	0.01	NC
ZrO_2	3.59	3.38	-5.99	3.25	0.57	-82.5
Sum	100.00	100.00	NC	100.00	100.00	NC

§ - Not a target constituent
* - DCP-AES measured values
$^{\$}$ - Target value
NC – Not calculated

Table 5.5. List of Glasses Discharged While Processing HWI-Al-19 Formulation.

Test	Date	Name	Mass (kg)	Cumulative Mass (kg)
1A	3/26/12	10V-G-106A	2.60	2.60
		10V-G-106B		
		10V-G-117A	3.70	6.30
		10V-G-117B		
		10V-G-118A	3.58	9.88
		10V-G-118B		
		10V-G-118C	3.14	13.02
	3/27/12	10V-G-119A		
		10V-G-119B	3.48	16.50
		10V-G-119C		
		10V-G-124A	2.92	19.42
		10V-G-124B		
		10V-G-125A	1.86	21.28
1B		10V-G-125B	3.84	25.12
		10V-G-125C		
		10V-G-125D	3.34	28.46
		10V-G-128A		
		10V-G-128B	3.34	31.80
		10V-G-129A		
		10V-G-129B	2.90	34.70
		10V-G-129C		
	3/28/12	10V-G-132A	3.22	37.92
		10V-G-132B		
		10V-G-132C	3.00	40.92
		10V-G-135A		
		10V-G-136A	2.08	43.00
1C		10V-G-136B	3.02	46.02
		10V-G-136C		
		10V-G-136D	3.06	49.08
		10V-G-136E		
		10V-G-137A	3.34	52.42
		10V-G-137B		
		10V-G-137C	3.32	55.74
		10V-G-137D		
		10V-G-139A	3.46	59.20
	3/29/12	10V-G-139B		

Table 5.5. List of Glasses Discharged While Processing HWI-Al-19 Formulation (Continued).

Test	Date	Name	Mass (kg)	Cumulative Mass (kg)
1C	3/29/12	10V-G-139C	3.72	62.92
		10V-G-139D		
		10V-G-143A	3.42	66.34
		10V-G-146A		
		10V-G-146B	2.80	69.14
		10V-G-146C		
1D		10V-G-148A	2.52	71.66
		10V-G-148B		
		10V-G-148C	3.52	75.18
		10V-G-149A		
		10V-G-149B	3.74	78.92
		10V-G-149C		
		10V-G-149D	3.62	82.54
		10V-G-149E		
	3/30/12	10V-G-151A	3.38	85.92
		10V-G-151B		
		10V-G-151C	4.36	90.28
		10W-G-08A	2.88	93.16
		10W-G-08B		
		10W-G-12A	1.38	94.54
1E		10W-G-16A	2.00	96.54
		10W-G-16B		
		10W-G-16C	3.68	100.22
		10W-G-16D		
		10W-G-16E	3.24	103.46
		10W-G-17A		
1F	4/10/12	10W-G-32A	4.04	107.50
		10W-G-32B		
		10W-G-33A	3.26	110.76
		10W-G-33B		
		10W-G-33C	2.24	113.00
		10W-G-33D		
		10W-G-33E	1.04	114.04
		10W-G-37A		
		10W-G-37B	1.06	115.10
	4/11/12	10W-G-37C		

Table 5.5. List of Glasses Discharged While Processing HWI-Al-19 Formulation (Continued).

Test	Date	Name	Mass (kg)	Cumulative Mass (kg)
1F	4/11/12	10W-G-37D	3.42	118.52
		10W-G-38A		
		10W-G-38B	2.96	121.48
		10W-G-38C		
		10W-G-40A	2.48	123.96
1G		10W-G-41A	3.52	127.48
		10W-G-41B		
		10W-G-41C	4.22	131.70
		10W-G-41D		
		10W-G-47A	3.64	135.34
		10W-G-47B		
		10W-G-47C	3.58	138.92
	4/12/12	10W-G-47D		
		10W-G-48A	3.70	142.62
		10W-G-48B		
		10W-G-48C	2.48	145.10
		10W-G-52A		
1H		10W-G-53A	3.80	148.90
		10W-G-53B		
		10W-G-53C	2.68	151.58
		10W-G-55A		
		10W-G-55B	1.88	153.46
	4/13/12	10W-G-60A		
		10W-G-60B	3.44	156.90
		10W-G-60C		
		10W-G-60D	2.44	159.34
		10W-G-61A		
		10W-G-61B	3.80	163.14
		10W-G-61C		
		10W-G-61D	4.30	167.44
		10W-G-61E		

Table 5.6. List of Glasses Discharged While Processing HLW-NG-Fe2 Formulation.

Test	Date	Name	Mass (kg)	Cumulative Mass (kg)
2A	4/16/12	10W-G-85A	2.97	2.97
		10W-G-86A		
		10W-G-86B	2.00	4.97
		10W-G-86C		
		10W-G-86D	2.22	7.19
		10W-G-86E		
		10W-G-87A	3.10	10.29
		10W-G-87B		
		10W-G-87C	3.58	13.87
		10W-G-87D		
	4/17/12	10W-G-92A	3.48	17.35
		10W-G-92B		
		10W-G-92C	3.40	20.75
		10W-G-92D		
		10W-G-93A	2.26	23.01
2B		10W-G-93B	3.48	26.49
		10W-G-98A		
		10W-G-98B	3.16	29.65
		10W-G-98C		
		10W-G-98D	3.10	32.75
		10W-G-98E		
		10W-G-98F	2.86	35.61
		10W-G-100A		
		10W-G-100B	2.80	38.41
	4/18/12	10W-G-100C		
		10W-G-100D	2.98	41.39
		10W-G-100E		
		10W-G-100F	2.74	44.13
		10W-G-104A		
2C		10W-G-105A	3.86	47.99
		10W-G-105B		
		10W-G-105C	3.22	51.21
		10W-G-109A		
		10W-G-109B	2.76	53.97
		10W-G-109C		

Table 5.6. List of Glasses Discharged While Processing HLW-NG-Fe2 Formulation (Continued).

Test	Date	Name	Mass (kg)	Cumulative Mass (kg)
2C	4/18/12	10W-G-111A	2.48	56.45
	4/19/12	10W-G-111B		
		10W-G-111C	3.18	59.63
		10W-G-111D		
		10W-G-111E	3.40	63.03
		10W-G-111F		
		10W-G-111G	3.12	66.15
		10W-G-116A		
2D		10W-G-116B	3.64	69.79
		10W-G-116C		
		10W-G-116D	3.30	73.09
		10W-G-116E		
		10W-G-127A	1.76	74.85

Table 5.7. List of Glasses Discharged While Processing HLWS-09 Formulation.

Test	Date	Name	Mass (kg)	Cumulative Mass (kg)
3A	6/25/2012	10X-G-126A	4.24	4.24
		10X-G-126B		
		10X-G-127A	2.08	6.32
	6/26/2012	10X-G-134A	4.38	10.70
		10X-G-134B		
		10X-G-134C	3.94	14.64
	6/27/2011	10X-G-134D		
		10X-G-138A	3.92	18.56
		10X-G-138B		
		10X-G-139A	4.18	22.74
		10X-G-144A		
3B		10X-G-145A	4.34	27.08
		10X-G-145B		
		10X-G-145C	3.90	30.98
		10X-G-146A		
		10X-G-146B	4.04	35.02
		10X-G-148A		
		10X-G-148B	3.16	38.18
	6/28/2012	10X-G-148C		
		10X-G-149A	3.44	41.62
		10X-G-149B		
		10X-G-151A	4.90	46.52
		10X-G-151B		
3C		10Y-G-10A	4.86	51.38
		10Y-G-16A		
		10Y-G-16B	3.46	54.84
		10Y-G-16C		
		10Y-G-17A	3.36	58.20
		10Y-G-17B		
		10Y-G-17C	3.16	61.36
		10Y-G-17D		
	6/29/2012	10Y-G-17E	3.56	64.92
		10Y-G-19A		
		10Y-G-19B	5.73	70.65
		10Y-G-23A		
		10Y-G-24A	1.86	72.51

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Table 5.7. List of Glasses Discharged While Processing HLWS-09 Formulation (Continued).

Test	Date	Name	Mass (kg)	Cumulative Mass (kg)
3A-2	6/29/2012	10Y-G-24B	4.36	76.87
		10Y-G-25A		
		10Y-G-25B	3.96	80.83
		10Y-G-28A		
3D	7/10/2012	10Y-G-39A	3.94	84.77
		10Y-G-39B		
		10Y-G-43A	3.78	88.55
		10Y-G-43B		
		10Y-G-44A	3.28	91.83
	7/11/12	10Y-G-44B		
		10Y-G-45A	3.48	95.31
		10Y-G-45B		
		10Y-G-45C	2.86	98.17
		10Y-G-45D		
		10Y-G-48A		
		10Y-G-51A	1.02	99.19
3E		10Y-G-52A	3.12	102.31
		10Y-G-55A	3.05	105.36
		10Y-G-57A		
		10Y-G-57B	4.04	109.40
		10Y-G-57C		
		10Y-G-57D	3.82	113.22
	7/12/12	10Y-G-59A		
		10Y-G-59B	3.24	116.46
		10Y-G-59C		
		10Y-G-62A	3.80	120.26
		10Y-G-63A		

Table 5.8. XRF Analyzed Compositions for Glass Discharged While Processing the HWI-Al-19 Formulation (wt%).

Test	1A							
Mass (kg)	Target	2.60	6.30	9.88	13.02	16.50	19.42	21.28
Constituents		10V-G-106B	10V-G-117B	10V-G-118B	10V-G-119A	10V-G-119C	10V-G-124B	10V-G-125A
Al_2O_3	23.92	11.05	13.54	17.96	19.95	21.03	22.45	23.07
$B_2O_3^*$	19.15	$12.36^{\$}$	14.46	15.87	16.76	17.46	17.89	18.10
BaO	0.05	<0.01	<0.01	<0.01	0.07	0.07	0.07	0.07
Bi_2O_3	1.14	0.27	0.44	0.73	0.85	0.88	0.96	1.06
CaO	5.57	6.46	6.21	5.94	5.72	5.57	5.48	5.59
CdO	0.02	0.01	0.02	0.03	0.03	0.03	0.03	0.04
Cr_2O_3	0.52	0.32	0.30	0.37	0.39	0.39	0.41	0.46
F	0.67	$0.11^{\#}$	0.18	$0.24^{\#}$	0.30	$0.36^{\#}$	0.37	0.37
Fe_2O_3	5.89	5.34	5.46	5.68	5.76	5.60	5.69	5.92
K_2O	0.14	0.40	0.38	0.30	0.21	0.24	0.16	0.21
Li_2O^*	3.56	$3.89^{\$}$	3.79	3.72	3.68	3.64	3.62	3.61
MgO	0.12	1.84	1.54	1.07	0.79	0.72	0.59	0.48
MnO	§	0.02	0.02	0.03	0.03	0.02	0.03	0.03
Na_2O	9.56	9.55	9.95	10.06	10.32	10.60	10.67	10.36
NiO	0.40	0.15	0.20	0.25	0.32	0.31	0.31	0.33
P_2O_5	1.05	0.40	0.52	0.76	0.89	0.95	1.05	1.12
PbO	0.41	0.09	0.15	0.24	0.27	0.29	0.32	0.35
SiO_2	26.95	41.94	37.93	33.28	31.01	29.53	28.04	27.24
SO_3	0.40	0.12	0.15	0.17	0.20	0.21	0.23	0.11
TiO_2	0.01	1.17	1.01	0.66	0.53	0.43	0.33	0.30
ZnO	0.08	2.29	1.90	1.27	0.90	0.73	0.52	0.45
ZrO_2	0.39	2.22	1.86	1.37	1.05	0.94	0.76	0.70
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.

$ - DCP-AES results

§ - Not a target constituent

\# - F was measured by XRF, values for other samples calculated by linear interpolation.

Table 5.8. XRF Analyzed Compositions for Glass Discharged While Processing the HWI-Al-19 Formulation (wt%) (Continued).

Test	1B							
Mass (kg)	Target	25.12	28.46	31.80	34.70	37.92	40.92	43.00
Constituents		10V-G-125C	10V-G-128A	10V-G-129A	10V-G-129C	10V-G-132B	10V-G-135A	10V-G-136A
Al_2O_3	23.92	23.57	23.95	24.11	24.60	24.80	24.64	24.62
B_2O_3[*]	19.15	18.44	18.64	18.79	18.88	18.95	19.01	19.03
BaO	0.05	0.09	0.08	0.08	0.07	0.08	0.08	0.08
Bi_2O_3	1.14	1.08	1.17	1.20	1.19	1.14	1.23	1.24
CaO	5.57	5.42	5.62	5.55	5.53	5.31	5.55	5.57
CdO	0.02	0.04	0.05	0.05	0.04	0.04	0.04	0.05
Cr_2O_3	0.52	0.44	0.45	0.44	0.44	0.45	0.45	0.45
F	0.67	0.38[#]	0.38	0.38	0.38[#]	0.40	0.41	0.42[#]
Fe_2O_3	5.89	5.86	6.10	6.20	6.07	5.89	6.19	6.18
K_2O	0.14	0.19	0.09	0.23	0.22	0.18	0.19	0.21
Li_2O[*]	3.56	3.60	3.59	3.58	3.58	3.57	3.57	3.57
MgO	0.12	0.38	0.28	0.33	0.30	0.28	0.28	0.25
MnO	§	0.02	0.02	0.03	0.02	0.03	0.02	0.03
Na_2O	9.56	10.65	10.20	10.35	10.26	10.58	10.21	10.24
NiO	0.40	0.31	0.35	0.35	0.34	0.33	0.35	0.36
P_2O_5	1.05	1.09	1.11	1.12	1.16	1.15	1.18	1.13
PbO	0.41	0.35	0.37	0.40	0.36	0.37	0.40	0.40
SiO_2	26.95	26.62	26.07	25.53	25.35	25.30	25.04	25.04
SO_3	0.40	0.31	0.38	0.34	0.36	0.38	0.37	0.38
TiO_2	0.01	0.23	0.22	0.20	0.18	0.15	0.15	0.14
ZnO	0.08	0.33	0.28	0.22	0.19	0.16	0.15	0.15
ZrO_2	0.39	0.61	0.59	0.54	0.49	0.46	0.47	0.46
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.
§ - Not a target constituent
[#] - F was measured by XRF, values for other samples calculated by interpolation

Table 5.8. XRF Analyzed Compositions for Glass Discharged While Processing the HWI-Al-19 Formulation (wt%) (Continued).

Test	1C								
Mass (kg)	Target	46.02	49.08	52.42	55.74	59.20	62.92	66.34	69.14
Constituents		10V-G-136C	10V-G-136E	10V-G-137B	10V-G-137D	10V-G-139B	10V-G-139D	10V-G-146A	10V-G-146C
Al_2O_3	23.83	24.59	24.61	24.74	23.85	24.49	24.22	24.45	24.35
B_2O_3[*]	19.08	18.99	19.01	19.03	19.04	19.05	19.06	19.07	19.07
BaO	0.05	0.09	0.10	0.08	0.11	0.07	0.09	0.10	0.08
Bi_2O_3	1.13	1.27	1.26	1.28	1.27	1.27	1.24	1.25	1.24
CaO	5.55	5.50	5.54	5.58	5.62	5.54	5.56	5.42	5.57
CdO	0.02	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.05
Cr_2O_3	0.52	0.44	0.47	0.46	0.41	0.44	0.44	0.42	0.46
F	0.67	0.41	0.40	0.39[#]	0.40	0.42	0.44[#]	0.42	0.42
Fe_2O_3	5.87	6.31	6.10	6.20	6.21	6.17	6.22	6.13	6.31
K_2O	0.14	0.16	0.14	0.11	0.07	0.15	0.17	0.08	0.18
Li_2O[*]	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55
MgO	0.12	0.24	0.26	0.23	0.24	0.23	0.20	0.24	0.24
MnO	§	0.02	0.03	0.02	0.02	0.03	0.03	0.02	0.02
Na_2O	9.52	10.30	10.44	10.18	10.44	10.26	10.32	10.43	10.51
NiO	0.40	0.35	0.35	0.37	0.37	0.37	0.37	0.35	0.37
P_2O_5	1.04	1.17	1.21	1.20	1.19	1.23	1.18	1.18	1.21
PbO	0.41	0.42	0.40	0.41	0.41	0.43	0.39	0.40	0.41
SiO_2	26.84	25.03	24.98	25.02	25.54	25.04	25.27	25.34	24.78
SO_3	0.8	0.40	0.42	0.45	0.46	0.54	0.54	0.49	0.54
TiO_2	0.01	0.12	0.12	0.13	0.13	0.12	0.13	0.11	0.12
ZnO	0.08	0.13	0.13	0.11	0.16	0.12	0.10	0.10	0.10
ZrO_2	0.39	0.46	0.45	0.44	0.47	0.45	0.44	0.42	0.43
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[*] Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.

§ - Not a target constituent

[#] - F was measured by XRF, values for other samples calculated by interpolation

Table 5.8. XRF Analyzed Compositions for Glass Discharged While Processing the HWI-Al-19 Formulation (wt%) (Continued).

Test	1D								
Mass (kg)		71.66	75.18	78.92	82.54	85.92	90.28	93.16	94.54
Constituents	Target	10V-G-148B	10V-G-149A	10V-G-149C	10V-G-149E	10V-G-151B	10V-G-151C	10W-G-08B	10W-G-12A
Al_2O_3	23.78	24.32	24.39	24.22	24.18	23.99	24.12	24.15	23.89
$B_2O_3^*$	19.04	19.03	19.03	19.03	19.04	19.04	19.04	19.04	19.04
BaO	0.05	0.09	0.08	0.10	0.08	0.08	0.09	0.11	0.09
Bi_2O_3	1.13	1.28	1.28	1.26	1.30	1.28	1.31	1.28	1.26
CaO	5.54	5.62	5.57	5.53	5.48	5.61	5.67	5.55	5.60
CdO	0.02	0.05	0.04	0.05	0.05	0.05	0.04	0.05	0.04
Cr_2O_3	0.52	0.46	0.45	0.43	0.48	0.43	0.46	0.46	0.45
F	0.66	$0.41^{\#}$	0.41	0.42	0.42	$0.43^{\#}$	0.43	0.43	0.42
Fe_2O_3	5.85	6.40	6.30	6.26	6.37	6.25	6.29	6.34	6.37
K_2O	0.14	0.05	0.19	0.16	0.16	0.13	0.20	0.14	0.20
Li_2O^*	3.54	3.54	3.54	3.54	3.54	3.54	3.54	3.54	3.54
MgO	0.12	0.23	0.23	0.22	0.23	0.23	0.18	0.22	0.21
MnO	§	0.02	0.03	0.03	0.03	0.02	0.02	0.03	0.02
Na_2O	9.50	10.46	10.42	10.49	10.22	10.27	10.45	10.12	10.27
NiO	0.40	0.36	0.36	0.37	0.35	0.38	0.36	0.37	0.38
P_2O_5	1.04	1.19	1.24	1.18	1.21	1.23	1.20	1.22	1.22
PbO	0.41	0.42	0.42	0.42	0.43	0.41	0.41	0.42	0.41
SiO_2	26.79	24.92	24.83	25.01	25.14	25.40	24.87	25.23	25.28
SO_3	1.00	0.50	0.55	0.65	0.65	0.63	0.66	0.66	0.66
TiO_2	0.01	0.11	0.12	0.11	0.10	0.11	0.11	0.12	0.12
ZnO	0.08	0.11	0.09	0.10	0.10	0.09	0.09	0.09	0.09
ZrO_2	0.39	0.43	0.43	0.44	0.43	0.43	0.44	0.43	0.43
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.
§ - Not a target constituent
$^{\#}$ - F was measured by XRF, values for other samples calculated by interpolation

Table 5.8. XRF Analyzed Compositions for Glass Discharged While Processing the HWI-Al-19 Formulation (wt%) (Continued).

Test	1E				1F				
Mass (kg)	Target	96.54	100.22	103.46	Target	107.50	110.76	113.00	114.04
Constituents		10W-G-16B	10W-G-16D	10W-G-17A		10W-G-32B	10W-G-33B	10W-G-33D	10W-G-37A
Al_2O_3	23.71	23.89	24.02	24.05	23.64	25.01	25.72	26.03	26.38
B_2O_3*	18.98	18.98	18.98	18.98	18.92	18.92	18.92	18.92	18.92
BaO	0.05	0.10	0.08	0.07	0.05	0.08	0.08	0.08	0.09
Bi_2O_3	1.13	1.30	1.30	1.35	1.12	1.18	1.15	1.18	1.12
CaO	5.52	5.60	5.61	5.65	5.50	5.27	5.26	5.20	5.04
CdO	0.02	0.04	0.04	0.04	0.02	0.03	0.05	0.04	0.04
Cr_2O_3	0.51	0.45	0.42	0.43	0.51	0.35	0.38	0.40	0.41
F	0.66	$0.42^{\#}$	0.39	0.36	0.66	0.32	$0.28^{\#}$	0.33	0.34
Fe_2O_3	5.84	6.43	6.41	6.57	5.82	5.65	5.65	5.76	5.52
K_2O	0.14	0.17	0.18	0.09	0.14	0.17	0.22	0.05	0.17
Li_2O*	3.53	3.53	3.53	3.53	3.52	3.52	3.52	3.52	3.52
MgO	0.12	0.25	0.19	0.19	0.12	0.25	0.25	0.22	0.22
MnO	§	0.03	0.03	0.03	§	0.02	0.02	0.02	0.02
Na_2O	9.48	10.27	10.46	10.13	9.45	11.04	10.50	10.33	10.04
NiO	0.40	0.38	0.38	0.38	0.39	0.27	0.29	0.31	0.30
P_2O_5	1.04	1.20	1.25	1.25	1.04	1.20	1.14	1.11	1.11
PbO	0.41	0.43	0.43	0.44	0.40	0.39	0.38	0.36	0.36
SiO_2	26.71	25.20	24.86	25.00	26.62	25.33	24.96	24.73	24.97
SO_3	1.30	0.69	0.82	0.82	1.60	0.36	0.60	0.80	0.84
TiO_2	0.01	0.12	0.10	0.11	0.01	0.12	0.13	0.12	0.11
ZnO	0.08	0.10	0.09	0.10	0.08	0.11	0.10	0.09	0.10
ZrO_2	0.39	0.44	0.43	0.44	0.39	0.42	0.40	0.40	0.39
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.

§ - Not a target constituent

$^{\#}$- F was measured by XRF, values for other samples calculated by interpolation

Table 5.8. XRF Analyzed Compositions for Glass Discharged While Processing the HWI-Al-19 Formulation (wt%) (Continued).

Test	1F					1G			
Mass (kg)	Target	115.10	118.52	121.48	123.96	Target	127.48	131.70	135.34
Constituents		10W-G-37C	10W-G-38A	10W-G-38C	10W-G-40A		10W-G-41B	10W-G-41D	10W-G-47B
Al_2O_3	23.64	26.57	26.47	26.69	26.61	23.68	26.03	25.26	24.89
B_2O_3*	18.92	18.92	18.92	18.92	18.92	18.96	18.96	18.96	18.96
BaO	0.05	0.09	0.07	0.08	0.08	0.05	0.07	0.08	0.06
Bi_2O_3	1.12	1.11	1.14	1.16	1.13	1.13	1.13	1.14	1.15
CaO	5.50	5.13	5.10	5.15	4.98	5.51	5.03	5.11	5.12
CdO	0.02	0.04	0.05	0.04	0.04	0.02	0.04	0.04	0.03
Cr_2O_3	0.51	0.41	0.41	0.43	0.42	0.51	0.41	0.44	0.43
F	0.66	0.36	$0.43^{\#}$	0.42	0.42	0.66	0.41	$0.40^{\#}$	0.41
Fe_2O_3	5.82	5.57	5.59	5.67	5.65	5.83	5.61	5.61	5.76
K_2O	0.14	0.17	0.20	0.12	0.18	0.14	0.15	0.18	0.16
Li_2O*	3.52	3.52	3.52	3.52	3.52	3.53	3.53	3.53	3.53
MgO	0.12	0.20	0.21	0.22	0.21	0.12	0.21	0.20	0.23
MnO	§	0.02	0.02	0.03	0.02	§	0.03	0.01	0.02
Na_2O	9.45	9.76	9.94	9.68	10.29	9.47	10.60	10.83	10.71
NiO	0.39	0.33	0.30	0.32	0.31	0.40	0.31	0.32	0.33
P_2O_5	1.04	1.13	1.12	1.16	1.12	1.04	1.12	1.11	1.13
PbO	0.40	0.37	0.36	0.38	0.37	0.41	0.37	0.38	0.38
SiO_2	26.62	24.70	24.57	24.44	24.29	26.68	24.59	25.05	25.31
SO_3	1.60	1.03	0.97	0.98	0.86	1.40	0.83	0.79	0.81
TiO_2	0.01	0.11	0.12	0.11	0.11	0.01	0.11	0.11	0.12
ZnO	0.08	0.09	0.09	0.09	0.09	0.08	0.09	0.09	0.08
ZrO_2	0.39	0.38	0.39	0.40	0.38	0.39	0.39	0.38	0.39
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.

§ - Not a target constituent

$^{\#}$- F was measured by XRF, values for other samples calculated by interpolation

Table 5.8. XRF Analyzed Compositions for Glass Discharged While Processing the HWI-Al-19 Formulation (wt%) (Continued).

Test	1G				1H				
Mass (kg)	Target	138.92	142.62	145.10	Target	148.90	151.58	153.46	156.90
Constituents		10W-G-47D	10W-G-48B	10W-G-52A		10W-G-53B	10W-G-55A	10W-G-60A	10W-G-60C
Al_2O_3	23.68	24.23	24.05	23.83	23.71	24.69	25.33	25.50	25.58
B_2O_3*	18.96	18.96	18.96	18.96	18.98	18.98	18.98	18.98	18.98
BaO	0.05	0.11	0.06	0.08	0.05	0.06	0.06	0.08	0.09
Bi_2O_3	1.13	1.16	1.19	1.20	1.13	1.17	1.18	1.15	1.09
CaO	5.51	5.20	5.25	5.36	5.52	5.40	5.19	5.10	5.08
CdO	0.02	0.04	0.04	0.03	0.02	0.04	0.04	0.04	0.04
Cr_2O_3	0.51	0.42	0.42	0.44	0.51	0.40	0.43	0.42	0.45
F	0.66	0.43	0.45	0.46$^{\#}$	0.66	0.44	0.42	0.40	0.38$^{\#}$
Fe_2O_3	5.83	5.84	5.80	5.95	5.84	5.84	5.77	5.73	5.65
K_2O	0.14	0.16	0.15	0.13	0.14	0.17	0.08	0.12	0.17
Li_2O*	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53
MgO	0.12	0.21	0.18	0.18	0.12	0.21	0.23	0.24	0.19
MnO	§	0.02	0.03	0.03	§	0.02	0.02	0.02	0.02
Na_2O	9.47	10.65	10.56	10.44	9.48	10.37	10.20	10.13	10.07
NiO	0.40	0.34	0.36	0.37	0.40	0.35	0.35	0.33	0.35
P_2O_5	1.04	1.12	1.16	1.14	1.04	1.14	1.12	1.15	1.16
PbO	0.41	0.37	0.38	0.39	0.41	0.39	0.37	0.36	0.35
SiO_2	26.68	25.72	25.90	26.01	26.71	25.60	25.36	25.38	25.43
SO_3	1.40	0.91	0.94	0.88	1.30	0.60	0.75	0.79	0.82
TiO_2	0.01	0.10	0.10	0.11	0.01	0.12	0.11	0.11	0.11
ZnO	0.08	0.08	0.09	0.08	0.08	0.09	0.09	0.08	0.08
ZrO_2	0.39	0.39	0.40	0.39	0.39	0.39	0.39	0.38	0.38
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.

§ - Not a target constituent

$^{\#}$- F was measured by XRF, values for other samples calculated by interpolation

Table 5.8. XRF Analyzed Compositions for Glass Discharged While Processing the HWI-Al-19 (wt%) Formulation (Continued).

Test	1H				All glass	
Mass (kg)	Target	159.34	163.14	167.44	Average	% Deviation from 1A Target
Constituents		10W-G-61A	10W-G-61C	10W-G-61E		
Al_2O_3	23.71	25.65	25.77	26.08	24.00	0.33
B_2O_3*	18.98	18.98	18.98	18.98	18.60	-2.91
BaO	0.05	0.06	0.08	0.07	0.08	NC
Bi_2O_3	1.13	1.18	1.12	1.07	1.14	0.57
CaO	5.52	5.21	5.06	4.96	5.44	-2.41
CdO	0.02	0.04	0.04	0.04	0.04	NC
Ce_2O_3	§	0.02	<0.01	0.02	NC	NC
Cr_2O_3	0.51	0.44	0.44	0.40	0.43	NC
F	0.66	0.37	0.36	0.35[#]	0.38	NC
Fe_2O_3	5.84	5.81	5.65	5.42	5.94	0.95
K_2O	0.14	0.21	0.04	0.13	0.17	NC
Li_2O*	3.53	3.53	3.53	3.53	3.56	-0.01
MgO	0.12	0.21	0.17	0.24	0.33	NC
MnO	§	0.02	0.02	0.02	0.02	NC
Na_2O	9.48	9.79	10.45	10.88	10.33	8.00
NiO	0.40	0.33	0.34	0.33	0.33	NC
P_2O_5	1.04	1.15	1.11	1.11	1.12	6.67
PbO	0.41	0.38	0.35	0.36	0.37	NC
SiO_2	26.71	25.23	25.12	24.79	26.15	-2.97
SO_3	1.30	0.80	0.78	0.69	0.59	NC
TiO_2	0.01	0.11	0.11	0.10	0.19	NC
ZnO	0.08	0.08	0.08	0.08	0.25	NC
ZrO_2	0.39	0.39	0.38	0.36	0.54	NC
Sum	100.00	100.00	100.00	100.00	100.00	NC

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.

§ - Not a target constituent

[#] - F was measured by XRF, values for other samples calculated by interpolation

Table 5.9. XRF Analyzed Compositions for Glass Discharged While Processing the HLW-NG-Fe2 Formulation (wt%).

Test		2A							
Mass (kg)		2.97	4.97	7.19	10.29	13.87	17.35	20.75	23.01
Constituents	Target	10W-G-86A	10W-G-86C	10W-G-86E	10W-G-87B	10W-G-87D	10W-G-92B	10W-G-92D	10W-G-93A
Al_2O_3	5.56	9.40	8.58	8.04	7.49	7.31	6.98	6.68	6.73
B_2O_3*	13.74	15.28$	15.00	14.75	14.48	14.26	14.11	14.00	13.95
BaO	0.08	0.13	0.11	0.13	0.12	0.13	0.10	0.14	0.14
Bi_2O_3	§	0.19	0.13	0.11	0.09	0.07	0.07	0.04	0.04
CaO	0.52	1.40	1.13	1.05	0.96	0.88	0.82	0.74	0.73
CdO	§	0.04	0.03	0.04	0.03	0.03	0.03	0.03	0.03
Ce_2O_3	0.11	0.08	0.09	0.10	0.08	0.09	0.10	0.09	0.08
Cr_2O_3	0.25	0.23	0.22	0.24	0.24	0.23	0.24	0.23	0.28
Fe_2O_3	15.93	14.18	13.71	14.40	14.53	14.69	15.22	15.09	14.76
K_2O	§	0.26	0.28	0.30	0.35	0.35	0.30	0.31	0.32
La_2O_3	0.09	0.09	0.08	0.07	0.08	0.09	0.08	0.10	0.08
Li_2O*	1.54	1.92$	1.85	1.79	1.72	1.67	1.63	1.61	1.59
MgO	0.16	0.31	0.34	0.32	0.30	0.32	0.29	0.30	0.32
MnO	3.21	1.82	2.03	2.17	2.26	2.40	2.51	2.55	2.44
Na_2O	14.09	13.59	13.74	13.33	13.47	13.09	13.04	13.39	13.62
NiO	0.47	0.30	0.35	0.37	0.40	0.41	0.43	0.48	0.45
P_2O_5	0.64	0.71	0.67	0.68	0.62	0.63	0.66	0.58	0.60
PbO	0.62	0.46	0.43	0.45	0.48	0.49	0.49	0.50	0.48
SiO_2	40.85	37.90	39.55	39.90	40.50	41.03	41.01	41.27	41.56
SnO_2	0.07	0.07	0.06	0.08	0.09	0.09	0.08	0.08	0.08
SO_3	0.70	0.23	0.37	0.38	0.43	0.42	0.47	0.46	0.43
SrO	0.19	0.14	0.14	0.15	0.15	0.16	0.17	0.16	0.15
TiO_2	§	0.11	0.10	0.10	0.08	0.08	0.08	0.08	0.09
ZnO	0.03	0.15	0.11	0.10	0.10	0.11	0.09	0.09	0.09
ZrO_2	1.12	0.98	0.90	0.95	0.95	0.96	0.99	1.00	0.95
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.
$ - DCP-AES results
§ - Not a target constituent
NA – Not analyzed

Table 5.9. XRF Analyzed Compositions for Glass Discharged While Processing the HLW-NG-Fe2 Formulation (wt%) (Continued).

Test		2B						
Mass (kg)		26.49	29.65	32.75	35.61	38.41	41.39	44.13
Constituents	Target	10W-G-98A	10W-G-98C	10W-G-98E	10W-G-100A	10W-G-100C	10W-G-100E	10W-G-104A
Al_2O_3	5.56	6.63	6.56	6.51	6.54	6.35	6.50	6.21
B_2O_3*	13.76	13.90	13.86	13.83	13.81	13.80	13.79	13.78
BaO	0.08	0.13	0.12	0.15	0.13	0.11	0.12	0.10
Bi_2O_3	§	0.03	0.02	0.02	0.02	0.02	0.02	0.01
CaO	0.52	0.71	0.65	0.63	0.66	0.65	0.63	0.64
CdO	§	0.03	0.02	0.02	0.03	0.03	0.02	0.02
Ce_2O_3	0.11	0.11	0.10	0.09	0.10	0.08	0.08	0.12
Cr_2O_3	0.25	0.31	0.28	0.26	0.27	0.26	0.23	0.26
Fe_2O_3	15.95	14.61	14.43	15.27	14.54	14.93	15.34	15.52
K_2O	§	0.29	0.31	0.34	0.41	0.37	0.31	0.34
La_2O_3	0.09	0.06	0.08	0.09	0.07	0.10	0.09	0.07
Li_2O*	1.54	1.58	1.57	1.56	1.56	1.56	1.55	1.55
MgO	0.16	0.32	0.34	0.30	0.31	0.33	0.32	0.29
MnO	3.21	2.39	2.41	2.50	2.42	2.57	2.63	2.68
Na_2O	14.11	13.74	14.03	13.31	13.47	13.41	12.91	13.05
NiO	0.47	0.47	0.45	0.46	0.46	0.47	0.49	0.49
P_2O_5	0.64	0.63	0.62	0.60	0.61	0.62	0.60	0.60
PbO	0.62	0.45	0.46	0.48	0.46	0.47	0.50	0.50
SiO_2	40.90	41.91	42.00	41.78	42.42	42.17	42.12	41.99
SnO_2	0.07	0.08	0.08	0.08	0.09	0.08	0.08	0.08
SO_3	0.60	0.37	0.38	0.39	0.39	0.37	0.36	0.35
SrO	0.19	0.15	0.15	0.16	0.15	0.16	0.17	0.18
TiO_2	§	0.07	0.07	0.09	0.07	0.07	0.08	0.07
ZnO	0.03	0.09	0.08	0.09	0.08	0.08	0.08	0.09
ZrO_2	1.12	0.92	0.91	0.97	0.93	0.95	0.97	0.99
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.
$ - DCP-AES results
§ - Not a target constituent
NA – Not analyzed

Table 5.9. XRF Analyzed Compositions for Glass Discharged While Processing the HLW-NG-Fe2 Formulation (wt%) (Continued).

Test		2C						
Mass (kg)		47.99	51.21	53.97	56.45	59.63	63.03	66.15
Constituents	Target	10W-G-105B	10W-G-109A	10W-G-109C	10W-G-111B	10W-G-111D	10W-G-111F	10W-G-116A
Al_2O_3	5.57	6.25	6.23	6.23	6.11	6.23	5.84	6.05
B_2O_3*	13.77	13.79	13.78	13.78	13.78	13.78	13.77	13.77
BaO	0.08	0.12	0.12	0.11	0.13	0.14	0.16	0.11
Bi_2O_3	§	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CaO	0.52	0.63	0.60	0.61	0.60	0.58	0.61	0.59
CdO	§	0.02	0.02	0.02	0.02	0.02	1.67	0.02
Ce_2O_3	0.11	0.12	0.08	0.11	0.09	0.10	0.10	0.08
Cr_2O_3	0.25	0.28	0.25	0.26	0.26	0.25	0.25	0.26
Fe_2O_3	15.96	14.89	15.09	14.95	14.98	15.15	15.98	15.51
K_2O	§	0.33	0.37	0.35	0.34	0.34	0.37	0.45
La_2O_3	0.09	0.10	0.08	0.08	0.09	0.10	0.13	0.10
Li_2O*	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55
MgO	0.16	0.32	0.32	0.34	0.33	0.28	0.28	0.33
MnO	3.21	2.48	2.57	2.57	2.60	2.55	2.78	2.61
Na_2O	14.12	13.56	13.52	13.67	13.74	13.38	12.71	13.24
NiO	0.47	0.48	0.45	0.47	0.45	0.45	0.49	0.48
P_2O_5	0.64	0.61	0.59	0.60	0.60	0.60	0.60	0.63
PbO	0.62	0.48	0.50	0.48	0.49	0.49	0.50	0.51
SiO_2	40.94	42.35	42.15	42.12	42.08	42.28	40.48	41.92
SnO_2	0.07	0.09	0.08	0.08	0.10	0.09	0.08	0.09
SO_3	0.50	0.25	0.34	0.34	0.38	0.36	0.32	0.36
SrO	0.19	0.16	0.16	0.16	0.16	0.16	0.17	0.17
TiO_2	§	0.08	0.08	0.08	0.07	0.09	0.08	0.09
ZnO	0.03	0.08	0.08	0.08	0.08	0.09	0.08	0.08
ZrO_2	1.12	0.95	0.96	0.95	0.97	0.97	1.00	1.00
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.
$ - DCP-AES results
§ - Not a target constituent
NA – Not analyzed

Table 5.9. XRF Analyzed Compositions for Glass Discharged While Processing the HLW-NG-Fe2 Formulation (wt%) (Continued).

Test		2D			All Glasses	
Mass (kg)		69.79	73.09	74.85	Average	% Dev. From Nominal Target
Constituents	Target	10W-G-116C	10W-G-116E	10W-G-127A		
Al_2O_3	5.57	6.13	6.18	6.16	6.72	20.93
B_2O_3*	13.78	13.84	13.84	13.84	14.02	NC
BaO	0.08	0.13	0.14	0.12	0.13	NC
Bi_2O_3	§	0.01	0.01	0.01	0.04	NC
CaO	0.52	0.62	0.58	0.59	0.73	NC
CdO	§	0.02	0.02	0.02	0.09	NC
Ce_2O_3	0.11	0.10	0.11	0.07	0.09	NC
Cr_2O_3	0.25	0.26	0.25	0.25	0.25	NC
Fe_2O_3	15.98	15.37	15.41	15.48	14.96	-6.08
K_2O	§	0.32	0.37	0.33	0.34	NC
La_2O_3	0.09	0.10	0.09	0.07	0.09	NC
Li_2O*	1.55	1.55	1.55	1.55	1.61	NC
MgO	0.16	0.32	0.33	0.30	0.31	NC
MnO	3.21	2.70	2.66	2.58	2.47	-22.86
Na_2O	14.14	13.22	13.38	13.17	13.39	-6.23
NiO	0.47	0.47	0.50	0.48	0.45	NC
P_2O_5	0.64	0.59	0.57	0.62	0.62	NC
PbO	0.62	0.51	0.49	0.51	0.48	NC
SiO_2	40.98	41.99	41.79	42.09	41.46	1.48
SnO_2	0.07	0.09	0.08	0.09	0.08	NC
SO_3	0.40	0.34	0.32	0.36	0.37	NC
SrO	0.19	0.16	0.17	0.17	0.16	NC
TiO_2	§	0.08	0.08	0.09	0.08	NC
ZnO	0.03	0.08	0.08	0.08	0.09	NC
ZrO_2	1.12	1.00	1.00	0.99	0.96	-13.77
Sum	100.00	100.00	100.00	100.00	100.00	NC

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass sample and feed sample using a simple well stirred tank model.
$ - DCP-AES results
§ - Not a target constituent
NA – Not analyzed

Table 5.10. XRF Analyzed Compositions for Glass Discharged While Processing the HLWS-09 Formulation (wt%)

Test	3A								3B	
Mass (kg)	Target	4.24	6.32	10.70	14.64	18.56	22.74		Target	27.08
Constituents		10X-G-126B	10X-G-127A	10X-G-134B	10X-G-134D	10X-G-138B	10X-G-144A	% Dev		10X-G-145B
Al_2O_3	8.03	8.10	7.83	7.90	7.71	7.62	7.77	-3.22	8.22	7.67
As_2O_3	§	0.13	0.11	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01
B_2O_3*	8.54	8.91$^{\$}$	8.84	8.73	8.67	8.63	8.60	0.68	7.96	8.37
Bi_2O_3	1.95	0.62	0.89	1.33	1.63	1.92	1.80	-7.80	2.30	2.00
CaO	8.45	2.95	3.87	5.63	6.71	7.60	7.50	-11.22	7.98	7.80
CdO	§	0.16	0.16	0.10	0.06	0.04	0.03	NC	§	0.02
Cl	§	0.02	0.01	0.01	0.02	0.01	0.02	NC	§	0.02
Cr_2O_3	0.32	0.26	0.29	0.44	0.46	0.47	0.44	NC	0.38	0.50
CuO	§	0.07	0.04	0.04	0.03	0.02	0.02	NC	§	0.01
F	0.64	0.08$^{\#}$	0.10	0.15$^{\#}$	0.27	0.38$^{\#}$	0.40	NC	0.76	0.42$^{\#}$
Fe_2O_3	1.83	8.87	7.65	6.03	4.65	3.91	3.31	80.62	2.16	2.98
K_2O	0.68	0.10	0.19	0.40	0.54	0.74	0.67	NC	0.80	0.66
La_2O_3	0.55	0.37	0.44	0.50	0.55	0.57	0.58	NC	0.65	0.66
Li_2O*	5.00	3.56$^{\$}$	3.83	4.25	4.49	4.66	4.77	-4.53	4.65	4.73
MgO	0.20	0.77	0.71	0.60	0.43	0.37	0.36	NC	0.24	0.34
MnO	1.07	2.63	2.52	2.05	1.71	1.49	1.11	3.48	1.27	1.33
Na_2O	10.11	11.08	10.39	10.23	9.94	9.64	10.42	3.07	11.92	10.76
Nd_2O_3	§	0.08	0.08	0.05	0.03	0.05	<0.01	NC	§	<0.01
NiO	1.32	0.58	0.69	0.97	1.13	1.33	1.31	-0.93	1.56	1.42
P_2O_5	3.08	1.13	1.60	2.15	2.65	2.92	3.06	-0.47	3.63	3.49
PbO	0.09	0.26	0.22	0.19	0.16	0.15	0.14	NC	0.11	0.13
Sb_2O_3	§	0.11	0.18	0.12	0.00	0.11	<0.01	NC	§	0.02
SiO_2	41.29	45.07	44.23	42.96	43.03	41.89	42.18	2.16	38.74	41.11
SO_3	1.20	0.34	0.45	0.59	0.79	0.88	0.94	NC	1.42	0.97
SrO	§	0.54	0.46	0.31	0.20	0.14	0.10	NC	§	0.06
TiO_2	0.04	0.22	0.20	0.19	0.18	0.19	0.18	NC	0.05	0.17
V2O3	2.00	0.51	0.77	1.20	1.54	1.74	1.71	-14.30	1.86	1.86
ZnO	§	1.14	1.01	0.75	0.49	0.36	0.26	NC	§	0.20
ZrO_2	3.59	1.32	2.21	2.14	1.93	2.18	2.31	-35.77	3.36	2.28
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	NC	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass and target concentrations using a simple well stirred tank model.
§ - Not a target constituent
$^{\$}$ - DCP-AES result.
$^{\#}$- F was measured by XRF, values for other samples calculated by interpolation
NC - Not calculated

Table 5.10. XRF Analyzed Compositions for Glass Discharged While Processing the HLWS-09 Formulation (wt%) (Continued).

Test	3B							3C		
Mass (kg)	Target	30.98	35.02	38.18	41.62	46.52		Target	51.38	54.84
Sample		10X-G-146A	10X-G-148A	10X-G-148C	10X-G-149B	10X-G-151B	% Dev.		10Y-G-16A	10Y-G-16C
Al_2O_3	8.22	7.61	7.57	7.59	7.71	7.83	-4.77	8.41	7.86	7.81
As_2O_3	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	<0.01
B_2O_3*	7.96	8.24	8.15	8.09	8.05	8.02	0.75	7.37	7.77	7.65
Bi_2O_3	2.30	2.10	2.28	2.38	2.38	2.30	-0.01	2.65	2.37	2.51
CaO	7.98	7.93	8.08	8.14	8.15	8.11	1.68	7.50	8.11	8.29
CdO	§	0.01	0.01	<0.01	<0.01	<0.01	NC	§	<0.01	<0.01
Cl	§	0.02	0.02	0.01	0.02	0.02	NC	§	0.01	0.02
Cr_2O_3	0.38	0.49	0.54	0.54	0.56	0.48	NC	0.43	0.55	0.53
CuO	§	0.01	<0.01	<0.01	0.01	<0.01	NC	§	<0.01	<0.01
F	0.76	0.43	0.45	$0.46^{\#}$	0.45	0.44	NC	0.87	$0.43^{\#}$	0.44
Fe_2O_3	2.16	2.70	2.74	2.62	2.59	2.45	13.56	2.49	2.46	2.55
K_2O	0.80	0.79	0.65	0.70	0.73	0.72	NC	0.92	0.78	0.81
La_2O_3	0.65	0.68	0.59	0.73	0.72	0.81	NC	0.75	0.84	0.71
Li_2O*	4.65	4.71	4.69	4.68	4.67	4.66	0.24	4.31	4.53	4.46
MgO	0.24	0.31	0.27	0.30	0.29	0.27	NC	0.28	0.29	0.28
MnO	1.27	1.46	1.50	1.23	1.10	0.98	-22.84	1.46	1.26	1.45
Na_2O	11.92	10.56	10.25	10.46	10.84	11.32	-5.02	13.73	11.37	10.90
Nd_2O_3	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	<0.01
NiO	1.56	1.49	1.61	1.63	1.62	1.61	3.52	1.79	1.70	1.77
P_2O_5	3.63	3.64	3.67	3.59	3.70	3.72	2.62	4.18	3.91	4.03
PbO	0.11	0.12	0.12	0.12	0.12	0.11	NC	0.13	0.13	0.12
Sb_2O_3	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	<0.01
SiO_2	38.74	40.25	39.85	39.80	40.00	40.02	3.30	36.19	39.78	39.05
SO_3	1.42	0.99	1.00	1.04	1.06	1.03	NC	1.63	1.08	1.16
SrO	§	0.04	0.03	0.02	0.02	0.01	NC	§	0.01	0.01
TiO_2	0.05	0.17	0.17	0.17	0.16	0.17	NC	0.05	0.15	0.17
V2O3	1.86	1.84	1.85	1.84	1.85	1.84	-1.04	1.72	1.85	1.87
ZnO	§	0.16	0.12	0.09	0.08	0.06	NC	§	0.06	0.06
ZrO_2	3.36	3.26	3.80	3.74	3.10	3.00	-10.72	3.14	2.70	3.37
Sum	100.00	100.00	100.00	100.00	100.00	100.00	NC	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass and target concentrations using a simple well stirred tank model.
§ - Not a target constituent
$^{\#}$- F was measured by XRF, values for other samples calculated by interpolation
NC - Not calculated

Table 5.10. XRF Analyzed Compositions for Glass Discharged While Processing the HLWS-09 Formulation (wt%) (Continued).

Test	3C							3A-2		
Mass (kg)	Target	58.20	61.36	64.92	70.65	72.51		Target	76.87	80.83
Sample		10Y-G-17B	10Y-G-17D	10Y-G-19A	10Y-G-23A	10Y-G-24A	% Dev.		10Y-G-25A	10Y-G-28A
Al_2O_3	8.41	7.74	7.92	8.02	8.04	7.99	-5.03	8.03	7.90	7.86
As_2O_3	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	<0.01
B_2O_3*	7.37	7.57	7.52	7.48	7.43	7.42	0.65	8.54	7.82	8.05
Bi_2O_3	2.65	2.47	2.53	2.55	2.60	2.57	-3.02	1.95	2.57	2.50
CaO	7.50	7.89	7.85	7.86	7.94	7.90	5.29	8.45	8.03	8.46
CdO	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	<0.01
Cl	§	0.02	0.01	0.02	0.02	0.02	NC	§	0.02	0.01
Cr_2O_3	0.43	0.53	0.58	0.51	0.54	0.51	NC	0.32	0.51	0.49
CuO	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	<0.01
F	0.87	0.45	0.47	0.48	0.51	0.52#	NC	0.64	0.43	0.34
Fe_2O_3	2.49	2.47	2.57	2.61	2.52	2.55	2.34	1.83	2.54	2.42
K_2O	0.92	0.80	0.84	0.85	0.85	0.81	NC	0.68	0.81	0.76
La_2O_3	0.75	0.67	0.84	0.91	0.82	0.87	NC	0.55	0.83	0.78
Li_2O*	4.31	4.42	4.39	4.36	4.34	4.33	0.62	5.00	4.57	4.71
MgO	0.28	0.30	0.27	0.30	0.29	0.27	NC	0.20	0.27	0.27
MnO	1.46	1.55	1.42	1.22	1.05	0.98	-32.65	1.07	1.01	0.94
Na_2O	13.73	11.87	11.54	11.95	11.98	11.99	-12.61	10.11	11.37	11.07
Nd_2O_3	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	<0.01
NiO	1.79	1.72	1.80	1.75	1.83	1.78	-0.69	1.32	1.73	1.77
P_2O_5	4.18	3.93	4.05	4.13	4.17	4.21	0.74	3.08	3.93	3.75
PbO	0.13	0.14	0.12	0.12	0.12	0.13	NC	0.09	0.11	0.10
Sb_2O_3	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	<0.01
SiO_2	36.19	38.78	38.57	38.89	38.84	38.89	7.46	41.29	39.51	39.74
SO_3	1.63	1.08	1.08	1.15	1.22	1.19	NC	1.20	1.08	0.99
SrO	§	0.01	0.01	0.01	0.01	0.01	NC	§	0.01	0.01
TiO_2	0.05	0.17	0.16	0.17	0.16	0.17	NC	0.04	0.19	0.16
$V2O_3$	1.72	1.77	1.76	1.81	1.85	1.72	0.04	2.00	1.85	1.86
ZnO	§	0.06	0.06	0.04	0.04	0.04	NC	§	0.04	0.04
ZrO_2	3.14	3.60	3.64	2.82	2.85	3.12	-0.46	3.59	2.90	2.90
Sum	100.00	100.00	100.00	100.00	100.00	100.00	NC	100.00	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass and target concentrations using a simple well stirred tank model.
§ - Not a target constituent
# - F was measured by XRF, values for other samples calculated by interpolation
NC - Not calculated

Table 5.10. XRF Analyzed Compositions for Glass Discharged While Processing the HLWS-09 Formulation (wt%) (Continued).

Test	3D								3E	
Mass (kg)	Target	84.77	88.55	91.83	95.31	98.17	99.19		Target	102.31
Sample		10Y-G-39B	10Y-G-43B	10Y-G-44B	10Y-G-45B	10Y-G-48A	10Y-G-51A	Dev.		10Y-G-52A
Al_2O_3	7.98	8.10	7.81	7.70	7.53	7.46	7.64	-4.36	7.97	7.54
As_2O_3	§	0.07	0.07	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01
B_2O_3*	8.50	8.18	8.28	8.34	8.39	8.41	8.42	-0.88	8.48	8.43
Bi_2O_3	1.94	2.46	2.38	2.24	2.34	2.30	2.22	14.08	1.94	2.17
CaO	8.41	8.60	8.42	8.40	8.59	8.61	8.49	0.97	8.39	8.37
CdO	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01
Cl	§	<0.01	0.01	0.01	0.01	0.01	0.02	NC	§	0.02
Cr_2O_3	0.32	0.75	0.65	0.58	0.54	0.55	0.51	NC	0.32	0.53
CuO	§	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01
F	0.64	$0.26^{\#}$	0.29	0.31	0.34	$0.36^{\#}$	0.37	NC	0.64	0.39
Fe_2O_3	1.82	2.49	2.37	2.20	2.39	2.20	2.20	20.86	1.82	2.17
K_2O	0.67	0.78	0.74	0.67	0.72	0.74	0.72	NC	0.67	0.68
La_2O_3	0.55	0.71	0.75	0.70	0.69	0.65	0.73	NC	0.55	0.72
Li_2O*	4.97	4.79	4.84	4.88	4.91	4.92	4.93	-0.90	4.96	4.93
MgO	0.20	0.30	0.28	0.26	0.29	0.27	0.26	NC	0.20	0.28
MnO	1.07	1.06	1.24	1.16	1.15	0.99	0.90	-15.99	1.07	0.94
Na_2O	10.06	10.53	10.23	10.20	9.89	9.65	9.73	-3.30	10.04	9.81
Nd_2O_3	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01
NiO	1.31	1.62	1.52	1.57	1.60	1.59	1.54	16.90	1.31	1.52
P_2O_5	3.06	3.72	3.72	3.61	3.42	3.49	3.51	14.82	3.05	3.50
PbO	0.09	0.20	0.22	0.11	0.10	0.12	0.09	NC	0.09	0.09
Sb_2O_3	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01
SiO_2	41.08	39.84	40.26	40.82	40.35	40.93	40.93	-0.37	40.99	41.10
SO_3	1.71	0.83	1.06	1.18	1.23	1.31	1.35	NC	1.91	1.46
SrO	§	0.01	0.01	0.01	0.01	0.01	0.01	NC	§	0.01
TiO_2	0.04	0.17	0.17	0.17	0.17	0.17	0.18	NC	0.04	0.17
$V2O_3$	1.99	1.96	1.95	1.90	2.04	2.00	1.99	0.18	1.99	1.89
ZnO	§	0.11	0.08	0.06	0.05	0.04	0.04	NC	§	0.03
ZrO_2	3.57	2.45	2.65	2.92	3.25	3.21	3.23	-9.45	3.56	3.26
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	NC	100.00	100.00

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass and target concentrations using a simple well stirred tank model.
§ - Not a target constituent
$^{\#}$- F was measured by XRF, values for other samples calculated by interpolation
NC - Not calculated

Table 5.10. XRF Analyzed Compositions for Glass Discharged While Processing the HLWS-09 Formulation (wt%) (Continued).

Test	3E						
Mass (kg)	Target	105.36	109.40	113.22	116.46	120.26	
Sample		10Y-G-57A	10Y-G-57C	10Y-G-59A	10Y-G-59C	10Y-G-63A	% Dev.
Al_2O_3	7.97	7.51	7.55	7.35	7.39	7.50	-5.82
As_2O_3	§	0.05	0.05	<0.01	<0.01	<0.01	NC
B_2O_3*	8.48	8.44	8.45	8.46	8.47	8.47	-0.11
Bi_2O_3	1.94	2.10	2.09	2.07	2.19	2.10	8.23
CaO	8.39	8.26	8.20	8.47	8.49	8.45	0.66
CdO	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC
Cl	§	0.01	0.01	0.02	0.01	0.01	NC
Cr_2O_3	0.32	0.47	0.51	0.48	0.48	0.44	NC
CuO	§	<0.01	<0.01	0.01	<0.01	<0.01	NC
F	0.64	$0.41^{\#}$	0.42	0.42	$0.43^{\#}$	0.44	NC
Fe_2O_3	1.82	2.05	2.09	2.11	2.06	2.06	12.96
K_2O	0.67	0.62	0.63	0.64	0.64	0.62	NC
La_2O_3	0.55	0.74	0.71	0.65	0.61	0.71	NC
Li_2O*	4.96	4.94	4.95	4.95	4.96	4.96	-0.11
MgO	0.20	0.24	0.25	0.23	0.24	0.23	NC
MnO	1.07	0.91	1.07	1.16	1.07	0.81	NC
Na_2O	10.04	10.48	9.94	9.59	9.70	9.92	-1.19
Nd_2O_3	§	<0.01	<0.01	0.03	0.03	<0.01	NC
NiO	1.31	1.45	1.50	1.54	1.50	1.51	15.03
P_2O_5	3.05	3.60	3.77	3.70	3.44	3.17	3.82
PbO	0.09	0.11	0.19	0.09	0.09	0.10	NC
Sb_2O_3	§	<0.01	<0.01	<0.01	<0.01	<0.01	NC
SiO_2	40.99	41.08	40.90	40.93	41.07	41.50	1.24
SO_3	1.91	1.49	1.52	1.50	1.60	1.64	NC
SrO	§	0.01	0.01	0.01	0.00	0.01	NC
TiO_2	0.04	0.14	0.15	0.18	0.18	0.17	NC
V2O3	1.99	1.89	1.89	2.00	1.96	1.94	-2.11
ZnO	§	0.03	0.02	0.02	0.02	0.02	NC
ZrO_2	3.56	2.96	3.15	3.41	3.36	3.22	-9.58
Sum	100.00	100.00	100.00	100.00	100.00	100.00	NC

* Values calculated from B_2O_3 and Li_2O analysis by DCP-AES on the first discharged glass and target concentrations using a simple well stirred tank model.

§ - Not a target constituent

$^{\#}$ - F was measured by XRF, values for other samples calculated by interpolation

NC - Not calculated

Table 5.11. List of Glass Pool Samples Taken While Processing HWI-Al-19 Formulation.

Test	Date	Time	Sample ID	Location	Secondary Phases Observed	Depth of Glass Pool (inches)
Before 1A	3/26/12	11:56	10V-D-94A	Center	No	6.50
		12:08	10V-D-94B	North West	No	6.50
		12:12	10V-D-106A	South East	No	6.50
After 1A	3/27/12	8:48	10V-D-124A	Center	No	8.50
		8:51	10V-D-124B	North West	No	8.50
		8:52	10V-D-124C	South East	No	8.50
After 1B	3/28/2012	7:35	10V-D-135A	Center	No	9.00
		7:40	10V-D-135B	North West	No	9.00
		7:43	10V-D-135C	South East	No	9.00
After 1C	3/29/2012	10:19	10V-D-148A	Center	No	7.50
			10V-D-148B	North West	No	7.50
			10V-D-148C	South East	No	7.50
After 1D	3/30/2012	9:48	10W-D-12A	Center	No	6.50
			10W-D-12B	North West	No	6.50
			10W-D-12C	South East	No	6.50
After 1E		21:35	10W-D-17A	Center	No	7.25
			10W-D-17B	North West	No	7.25
			10W-D-17C	South East	No	7.25
	4/3/2012	10:36	10W-D-20A	Center	No	6.75
Before 1F	4/10/2012	9:00	10W-D-20B	Center	No	7.25
			10W-D-20C	South East	No	7.25
			10W-D-20D	North West	No	7.25
After 1F	4/11/2012	6:30	10W-D-40A	North West	Yes	No Data
			10W-D-40B	Center	No	No Data
			10W-D-40C	South East	Yes	No Data
		7:30	10W-D-40D	North West	No	No Data
		7:40	10W-D-40E	South East	Yes	No Data
		9:18	2 Unnamed Samples	North West + South East	No	8.75
After 1G	4/12/2012	7:24	10W-D-48A	North West	Yes	7.50
			10W-D-48B	Center	No	7.50
			10W-D-48C	South East	Yes	7.50
		9:15	2 Unnamed Samples	North West + South East	Yes	No Data
Before 1H		14:15	Dip sample	South East	No	No data
After 1H	4/13/2012	7:35	10W-D-66A	North West	No	7.25
		7:40	10W-D-66B	Center	No	7.25
		7:43	10W-D-66C	South East	Yes	7.25

Table 5.12. List of Glass Pool Samples Taken While Processing HLW-NG-Fe2 Formulation.

Test	Date	Time	Sample ID	Location	Secondary Phases Observed	Depth of Glass Pool (inches)
Before 2A	4/16/2012	7:40	10W-D-69A	Center	No	No Data
			10W-D-69B	South East	No	No Data
			10W-D-69C	North West	No	No Data
After 2A	4/17/2012	7:19	10W-D-92A	Center	No	No Data
			10W-D-92B	North West	Yes	No Data
			10W-D-92C	South East	Yes	No Data
		9:35	Unnamed Sample	South East	Yes	No Data
		10:30	3 Unnamed Samples	North West, Center and South West	No	8.00
After 2B	4/18/2012	7:56	10W-D-104A	Center	No	9.00
			10W-D-104B	North West	Yes	7.00
			10W-D-104C	South East	Yes	7.00
		11:42	10W-D-104D	Center	No	6.75
After 2C	4/19/2012	9:33	10W-D-114A	Center	No	8.00
			10W-D-114B	North West	No	8.00
			10W-D-114C	South East	No	8.00
After 2D		18:40	10W-D-127A	South East	Yes	6.50
			10W-D-127B	Center	No	6.50
			10W-D-127C	North West	No	6.50

Table 5.13. List of Glass Pool Samples Taken While Processing HLWS-09 Formulation.

Test	Date	Time	Sample ID	Location	Secondary Phases Observed	Depth of Glass Pool (inches)
Before 3A	6/22/2012	16:19	10X-D-112A	North	No	7.50
			10X-D-112B	East	No	7.50
			10X-D-112C	South	No	7.50
	6/25/2012	7:10	10X-D-112D	North	No	7.50
			10X-D-112E	Center	No	7.50
			10X-D-112F	South	No	7.50
After 3A	6/27/2012	9:05	10X-D-144A	North	No	8.00
			10X-D-144B	Center	No	8.00
			10X-D-144C	South	No	8.00
After 3B	6/28/2012	8:58	10Y-D-10A	North	No	7.75
			10Y-D-10B	Center	No	7.75
			10Y-D-10C	South	No	7.75
After 3C	6/29/2012	9:12	10Y-D-23A	North	No	8.50
			10Y-D-23B	Center	No	8.50
			10Y-D-23C	South	No	8.50
After 3A-2	6/29/2012	17:38	10Y-D-28A	North	No	8.50
			10Y-D-28B	Center	No	8.50
			10Y-D-28C	South	No	8.50
	7/10/2012	8:11	10Y-D-31A	North	No	7.50
			10Y-D-31B	Center	No	7.50
			10Y-D-31C	South	No	7.50
After 3D	7/11/2012	8:57	10Y-D-51A	North	No	7.25
			10Y-D-51B	Center	No	7.25
			10Y-D-51C	South	No	7.25
After 3E	7/12/2012	7:11	10Y-D-63A	North	No	9.00
			10Y-D-63B	Center	No	9.00
			10Y-D-63C	South	No	9.00

Table 5.14. XRF Analyzed Compositions for the Dip Samples Taken While Processing the HWI-Al-19 Formulation.

Test	Before 1A	After 1A		After 1B		After 1C		After 1D	
Constituent	10V-D-94A	Target	10V-D-124A	Target	10V-D-135A	Target	10V-D-148A	Target	10W-D-12A
Al_2O_3	6.53	23.92	22.30	23.88	24.65	23.83	24.28	23.78	23.99
B_2O_3	12.36*	19.15	18.10*	19.12	19.03*	19.08	19.07*	19.04	19.04*
BaO	<0.01	0.05	0.06	0.05	0.06	0.05	0.06	0.05	0.10
Bi_2O_3	<0.01	1.14	1.15	1.14	1.30	1.13	1.31	1.13	1.36
CaO	6.67	5.57	5.88	5.56	5.66	5.55	5.63	5.54	5.71
CdO	<0.01	0.02	0.03	0.02	0.04	0.02	0.04	0.02	0.04
Cr_2O_3	0.21	0.52	0.52	0.52	0.47	0.52	0.48	0.52	0.45
F	0.11*	0.67	0.37*	0.67	0.42*	0.67	0.42*	0.66	0.42*
Fe_2O_3	5.03	5.89	6.43	5.88	6.56	5.87	6.51	5.85	6.54
K_2O	0.62	0.14	0.22	0.14	0.17	0.14	0.24	0.14	0.20
Li_2O	3.89*	3.56	3.61*	3.56	3.57*	3.55	3.55*	3.54	3.54*
MgO	2.16	0.12	0.49	0.12	0.23	0.12	0.16	0.12	0.22
MnO	0.02	§	0.02	§	0.02	§	0.03	§	0.03
Na_2O	8.87	9.56	9.30	9.54	9.55	9.52	9.74	9.50	9.54
NiO	0.05	0.40	0.40	0.40	0.41	0.40	0.44	0.40	0.45
P_2O_5	0.19	1.05	1.09	1.05	1.23	1.04	1.32	1.04	1.29
PbO	0.00	0.41	0.36	0.41	0.44	0.41	0.44	0.41	0.43
SiO_2	45.89	26.95	27.63	26.89	24.96	26.84	25.06	26.79	25.27
SO_3	0.12	0.40	0.28	0.60	0.45	0.80	0.58	1.00	0.71
TiO_2	1.53	0.01	0.34	0.01	0.14	0.01	0.12	0.01	0.11
ZnO	3.03	0.08	0.57	0.08	0.15	0.08	0.11	0.08	0.10
ZrO_2	2.72	0.39	0.82	0.39	0.48	0.39	0.44	0.39	0.45
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

§ - Not a target constituent
* - Value from contemporaneous discharge.

Table 5.14. XRF Analyzed Compositions for the Dip Samples Taken While Processing the HWI-Al-19 Formulation (Continued).

Test	**After 1E**					**After 1F**	
Constituent	Target	10W-D-17A	10W-D-17B	10W-D-17C	10W-D-20A	Target	10W-D-40B
Al_2O_3	23.71	23.92	24.18	23.86	24.39	23.64	26.42
B_2O_3	18.98	18.98^*	18.98^*	18.98^*	18.98^*	18.92	18.92^*
BaO	0.05	0.07	0.08	0.11	0.09	0.05	0.08
Bi_2O_3	1.13	1.32	1.32	1.31	1.28	1.12	1.25
CaO	5.52	5.57	5.61	5.66	5.71	5.50	5.22
CdO	0.02	0.03	0.05	0.04	0.04	0.02	0.05
Cr_2O_3	0.51	0.48	0.43	0.45	0.28	0.51	0.48
F	0.66	0.36^*	0.36^*	0.36^*	0.36^*	0.66	0.42^*
Fe_2O_3	5.84	6.46	6.50	6.58	5.78	5.82	5.92
K_2O	0.14	0.18	0.07	0.20	0.18	0.14	0.15
Li_2O	3.53	3.53^*	3.53^*	3.53^*	3.53^*	3.52	3.52^*
MgO	0.12	0.24	0.23	0.23	0.24	0.12	0.19
MnO	§	0.03	0.03	0.03	0.03	§	0.03
Na_2O	9.48	10.23	10.12	10.27	10.54	9.45	9.04
NiO	0.40	0.38	0.45	0.40	0.26	0.39	0.36
P_2O_5	1.04	1.21	1.23	1.21	1.22	1.04	1.19
PbO	0.41	0.42	0.42	0.43	0.42	0.40	0.41
SiO_2	26.71	25.12	24.95	24.65	25.46	26.62	24.66
SO_3	1.30	0.82	0.80	1.04	0.56	1.60	1.06
TiO_2	0.01	0.11	0.12	0.13	0.12	0.01	0.12
ZnO	0.08	0.09	0.10	0.10	0.10	0.08	0.09
ZrO_2	0.39	0.45	0.44	0.44	0.44	0.39	0.42
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00

§ - Not a target constituent
* - Value from contemporaneous discharge.

Table 5.14. XRF Analyzed Compositions for the Dip Samples Taken While Processing the HWI-Al-19 Formulation (Continued).

Test	After 1G		After 1H	
Constituent	Target	10W-D-48B	Target	10W-D-66C
Al_2O_3	23.68	24.18	23.71	25.89
B_2O_3	18.96	18.96*	18.98	18.98*
BaO	0.05	0.07	0.05	0.08
Bi_2O_3	1.13	1.24	1.13	1.15
CaO	5.51	5.24	5.52	5.12
CdO	0.02	0.04	0.02	0.05
Cr_2O_3	0.51	0.44	0.51	0.45
F	0.66	0.46*	0.66	0.35*
Fe_2O_3	5.83	5.96	5.84	5.76
K_2O	0.14	0.11	0.14	0.07
Li_2O	3.53	3.53*	3.53	3.53*
MgO	0.12	0.22	0.12	0.21
MnO	§	0.04	§	0.02
Na_2O	9.47	9.90	9.48	10.07
NiO	0.40	0.38	0.40	0.37
P_2O_5	1.04	1.26	1.04	1.17
PbO	0.41	0.40	0.41	0.37
SiO_2	26.68	25.95	26.71	25.01
SO_3	1.40	1.07	1.30	0.79
TiO_2	0.01	0.11	0.01	0.11
ZnO	0.08	0.08	0.08	0.08
ZrO_2	0.39	0.39	0.39	0.39
Sum	100.00	100.00	100.00	100.00

§ - Not a target constituent
* - Value from contemporaneous discharge.

Table 5.15. XRF Analyzed Compositions for the Dip Samples Taken While Processing the HLW-NG-Fe2 Formulation.

Test	**Before 2A**	**After 2A**		**After 2B**	
Constituent	10W-D-69A	Target	10W-D-92A	Target	10W-D-104A
Al_2O_3	10.13	5.56	6.62	5.56	6.29
B_2O_3	15.28*	13.74	13.95*	13.76	13.78*
BaO	0.10	0.08	0.14	0.08	0.13
Bi_2O_3	0.25	§	0.03	§	0.01
CaO	1.58	0.52	0.72	0.52	0.64
CdO	0.05	§	0.02	§	0.03
Ce_2O_3	0.06	0.11	0.13	0.11	0.12
Cr_2O_3	0.20	0.25	0.25	0.25	0.27
Fe_2O_3	14.17	15.93	15.11	15.95	15.38
K_2O	0.27	§	0.35	§	0.35
La_2O_3	0.06	0.09	0.08	0.09	0.09
Li_2O	1.92*	1.54	1.59*	1.54	1.55*
MgO	0.31	0.16	0.26	0.16	0.31
MnO	1.64	3.21	2.43	3.21	2.53
Na_2O	12.85	14.09	12.49	14.11	12.48
NiO	0.26	0.47	0.45	0.47	0.49
P_2O_5	0.77	0.64	0.68	0.64	0.66
PbO	0.47	0.62	0.49	0.62	0.49
SiO_2	38.00	40.85	42.35	40.90	42.60
SnO_2	0.10	0.07	0.08	0.07	0.08
SO_3	0.17	0.70	0.48	0.60	0.42
SrO	0.13	0.19	0.16	0.19	0.17
TiO_2	0.11	§	0.08	§	0.08
ZnO	0.15	0.03	0.08	0.03	0.08
ZrO_2	0.97	1.12	0.97	1.12	0.99
Sum	100.00	100.00	100.00	100.00	100.00

§ - Not a target constituent
* - Value from contemporaneous discharge

Table 5.15. XRF Analyzed Compositions for the Dip Samples Taken While Processing the HLW-NG-Fe2 Formulation (Continued).

Test	**After 2C**		**After 2D**			
Constituent	Target	10W-D-114A	Target	10W-D-127A	10W-D-127B	10W-D-127C
Al_2O_3	5.57	6.13	5.57	6.19	6.22	6.09
B_2O_3	13.77	13.77*	13.78	13.79*	13.79*	13.79*
BaO	0.08	0.13	0.08	0.15	0.15	0.13
Bi_2O_3	§	0.01	§	0.01	0.01	<0.01
CaO	0.52	0.61	0.52	0.59	0.58	0.59
CdO	§	0.03	§	0.03	0.02	0.03
Ce_2O_3	0.11	0.12	0.11	0.11	0.12	0.12
Cr_2O_3	0.25	0.25	0.25	0.25	0.25	0.43
Fe_2O_3	15.96	15.69	15.98	15.12	15.16	15.73
K_2O	§	0.32	§	0.35	0.43	0.28
La_2O_3	0.09	0.09	0.09	0.10	0.11	0.10
Li_2O	1.55	1.55*	1.55	1.55*	1.55*	1.55*
MgO	0.16	0.31	0.17	0.32	0.30	0.30
MnO	3.21	2.54	3.22	2.64	2.61	2.69
Na_2O	14.12	12.34	14.14	13.52	13.35	12.98
NiO	0.47	0.50	0.47	0.51	0.50	0.57
P_2O_5	0.64	0.68	0.64	0.59	0.58	0.61
PbO	0.62	0.50	0.62	0.49	0.48	0.49
SiO_2	40.94	42.57	40.98	41.88	42.11	41.75
SnO_2	0.07	0.11	0.07	0.09	0.09	0.09
SO_3	0.50	0.39	0.40	0.45	0.33	0.37
SrO	0.19	0.17	0.19	0.17	0.16	0.17
TiO_2	§	0.09	§	0.09	0.08	0.07
ZnO	0.03	0.08	0.03	0.08	0.08	0.09
ZrO_2	1.12	1.00	1.12	0.97	0.96	0.99
Sum	100.00	100.00	100.00	100.00	100.00	100.00

§ - Not a target constituent

* - Value from contemporaneous discharge

Table 5.16. XRF Analyzed Compositions for the Dip Samples Taken While Processing the HLWS-09 Formulation.

Test	**Before 3A**		**After 3A**		**After 3B**		**After 3C**	
Constituent	10X-D-112A	10X-D-112E	Target	10X-D-144B	Target	10Y-D-10B	Target	10Y-D-23B
Al_2O_3	8.00	7.99	8.03	7.59	8.22	7.62	8.41	7.86
B_2O_3	8.91*	8.91*	8.54	8.60*	7.96	8.02*	7.37	7.42*
Bi_2O_3	0.09	0.10	1.95	2.01	2.30	2.49	2.65	2.80
CaO	0.81	0.85	8.45	7.86	7.98	8.44	7.50	8.11
CdO	0.24	0.26	§	0.03	§	<0.01	§	<0.01
Cr_2O_3	0.14	0.14	0.32	0.51	0.38	0.58	0.43	0.58
CuO	0.08	0.08	§	0.02	§	<0.01	§	0.01
F	0.08*	0.08*	0.64	0.40*	0.76	0.44*	0.87	0.52*
Fe_2O_3	11.17	11.53	1.83	3.47	2.16	2.63	2.49	2.73
K_2O	<0.01	<0.01	0.68	0.61	0.80	0.81	0.92	0.85
La_2O_3	0.25	0.30	0.55	0.64	0.65	0.82	0.75	0.88
Li_2O	3.56*	3.56*	5.00	4.77*	4.65	4.66*	4.31	4.33*
MgO	1.20	1.09	0.20	0.34	0.24	0.28	0.28	0.27
MnO	2.87	2.93	1.07	1.18	1.27	0.94	1.46	0.97
Na_2O	12.00	11.33	10.11	9.58	11.92	10.28	13.73	11.30
Nd_2O_3	0.13	0.14	§	<0.01	§	<0.01	§	<0.01
NiO	0.18	0.19	1.32	1.41	1.56	1.68	1.79	1.96
P_2O_5	0.22	0.20	3.08	3.12	3.63	3.72	4.18	4.05
PbO	0.29	0.30	0.09	0.15	0.11	0.13	0.13	0.14
Sb_2O_3	0.15	0.26	§	0.04	§	<0.01	§	<0.01
SiO_2	46.73	46.77	41.29	45.00	38.74	40.17	36.19	38.46
SO_3	0.02	0.01	1.20	0.92	1.42	1.06	1.63	1.24
SrO	0.75	0.77	§	0.10	§	0.01	§	0.01
TiO_2	0.23	0.24	0.04	0.18	0.05	0.15	0.05	0.17
V_2O_3	<0.01	<0.01	2.00	1.80	1.86	1.91	1.72	1.84
ZnO	1.53	1.57	§	0.26	§	0.07	§	0.04
ZrO_2	0.38	0.40	3.59	2.42	3.36	3.10	3.14	3.45
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

§ - Not a target constituent
* - Value from contemporaneous discharge

Table 5.16. XRF Analyzed Compositions for the Dip Samples Taken While Processing the HLWS-09 Formulation (Continued).

Test	**After 3A-2**			**After 3D**		**After 3E**	
Constituent	Target	10Y-D-28A	10Y-D-31B	Target	10Y-D-51B	Target	10Y-D-63B
Al_2O_3	8.03	7.73	8.05	7.98	7.48	7.97	7.30
B_2O_3	8.54	8.05*	8.05*	8.50	8.42*	8.48	8.47*
Bi_2O_3	1.95	2.64	2.58	1.94	2.29	1.94	2.27
CaO	8.45	8.56	8.38	8.41	8.70	8.39	8.69
CdO	§	<0.01	<0.01	§	<0.01	§	<0.01
Cr_2O_3	0.32	0.54	0.86	0.32	0.50	0.32	0.50
CuO	§	<0.01	<0.01	§	0.01	§	0.01
F	0.64	0.34*	0.34*	0.64	0.37*	0.64	0.44*
Fe_2O_3	1.83	2.51	2.68	1.82	2.21	1.82	2.20
K_2O	0.68	0.81	0.74	0.67	0.75	0.67	0.60
La_2O_3	0.55	0.81	0.73	0.55	0.67	0.55	0.73
Li_2O	5.00	4.71*	4.71*	4.97	4.93*	4.96	4.96*
MgO	0.20	0.24	0.32	0.20	0.25	0.20	0.22
MnO	1.07	1.00	1.03	1.07	0.88	1.07	0.89
Na_2O	10.11	10.51	10.19	10.06	9.47	10.04	9.14
Nd_2O_3	§	<0.01	<0.01	§	<0.01	§	<0.01
NiO	1.32	1.75	1.68	1.31	1.57	1.31	1.58
P_2O_5	3.08	3.74	3.64	3.06	3.46	3.05	3.15
PbO	0.09	0.14	0.11	0.09	0.12	0.09	0.11
Sb_2O_3	§	<0.01	<0.01	§	<0.01	§	<0.01
SiO_2	41.29	39.59	40.10	41.08	40.99	40.99	41.47
SO_3	1.20	1.01	0.64	1.71	1.31	1.91	1.62
SrO	§	0.01	0.01	§	0.01	§	0.01
TiO_2	0.04	0.17	0.18	0.04	0.18	0.04	0.16
V_2O_3	2.00	2.01	1.92	1.99	2.00	1.99	2.10
ZnO	§	0.04	0.14	§	0.04	§	0.02
ZrO_2	3.59	3.08	2.92	3.57	3.42	3.56	3.38
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00

§ - Not a target constituent
* - Value from contemporaneous discharge.

Table 5.17. XRF Analyzed Composition of Secondary Phase from Dip Sample Taken After Test 2B.

Constituent	Wt%
Al_2O_3	0.16
B_2O_3	NA
BaO	0.38
CaO	0.84
Ce_2O_3	<0.01
Cr_2O_3	0.21
Fe_2O_3	0.67
K_2O	1.10
La_2O_3	<0.01
Li_2O	NA
MgO	0.04
MnO	0.16
Na_2O	38.90
NiO	0.01
P_2O_5	0.78
PbO	0.04
SiO_2	0.65
SnO_2	<0.01
SO_3	55.57
SrO	0.47
ZnO	<0.01
ZrO_2	0.02
Sum	100.00

NA - Not Analyzed

Table 5.18. Concentrations [ppmv] of Selected Species in Off-Gas Measured by FTIR Spectroscopy while Processing the HWI-Al-19 Formulation.

Test	**1A**		**1B**		**1C**		**1D**		**1E**	
	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
N_2O	<1.0	<1.0 – 1.7	<1.0	<1.0 – 1.8	<1.0	<1.0 – 1.2	<1.0	<1.0 – 1.1	<1.0	<1.0 – 1.0
NO	26.7	14.0 – 68.8	26.7	2.6 – 66.9	28.1	2.7 – 51.0	27.6	<1.0 – 45.5	26.8	12.9 – 42.2
NO_2	6.4	2.9 – 16.6	5.6	<1.0 – 16.4	5.8	<1.0 – 9.6	5.8	<1.0 – 8.7	6.3	2.5 – 9.6
NH_3	<1.0	<1.0 – 2.6	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
H_2O [%]	1.8	1.1– 3.8	1.7	0.5 – 3.9	2.4	0.9 – 3.3	2.1	0.7 – 2.6	2.1	1.3 – 2.8
CO_2	719	580 - 1278	720	470 - 1255	729	479 - 937	731	461 - 926	720	585 - 842
Nitrous Acid	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
Nitric Acid	<1.0	<1.0 – 1.9	2.1	<1.0 – 2.7	2.3	<1.0 – 4.3	2.7	1.6 – 5.3	2.7	1.9 – 4.0
HCN	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
CO	1.1	<1.0 – 4.1	1.1	<1.0 – 2.2	1.1	<1.0 – 4.2	1.2	<1.0 – 2.1	1.2	<1.0 – 2.0
HCl	<1.0	NA	<1.0	<1.0 – 1.0	<1.0	NA	<1.0	NA	<1.0	NA
HF	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	<1.0 – 1.1	1.0	<1.0 – 1.2

NA : Not applicable.

Table 5.18. Concentrations [ppmv] of Selected Species in Off-Gas Measured by FTIR Spectroscopy while Processing the HWI-Al-19 Formulation (Continued).

Test	**1F**		**1G**		**1H**	
	Avg.	Range	Avg.	Range	Avg.	Range
N_2O	<1.0	<1.0 – 3.1	<1.0	<1.0 – 1.4	<1.0	<1.0 – 2.0
NO	26.0	6.5 – 110	25.9	<1.0 – 44.7	24.6	<1.0 – 80.7
NO_2	5.5	1.1 – 24.2	4.9	<1.0 – 8.2	4.3	<1.0 – 18.4
NH_3	<1.0	NA	<1.0	NA	<1.0	NA
H_2O [%]	1.8	0.9 – 5.3	1.9	0.5 – 2.6	1.8	0.6– 4.3
CO_2	704	477 - 1867	695	430 - 870	685	444 - 1447
Nitrous Acid	<1.0	NA	<1.0	NA	<1.0	NA
Nitric Acid	1.7	<1.0 – 4.1	2.4	<1.0 – 8.2	2.9	<1.0 – 5.0
HCN	<1.0	NA	<1.0	<1.0 – 5.7	<1.0	NA
CO	1.1	<1.0 – 6.0	1.0	<1.0 – 2.1	<1.0	<1.0 – 6.2
HCl	<1.0	NA	<1.0	NA	<1.0	NA
HF	<1.0	<1.0 – 1.5	<1.0	<1.0 – 1.3	1.1	<1.0 – 1.8

NA : Not applicable.

Table 5.19. Concentrations [ppmv] of Selected Species in Off-Gas Measured by FTIR Spectroscopy while Processing the HLW-NG-Fe2 Formulation.

Test	**2A**		**2B**		**2C**		**2D**	
	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
N_2O	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
NO	7.0	<1.0 – 10.2	6.8	<1.0 – 9.6	7.0	2.0 – 11.3	7.1	<1.0 – 9.5
NO_2	<1.0	<1.0 – 1.6	<1.0	<1.0 – 1.4	<1.0	<1.0 – 1.1	<1.0	NA
NH_3	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
H_2O [%]	2.8	0.5 – 3.6	2.1	1.0 – 3.0	2.5	1.5 – 3.8	2.5	1.1 – 2.9
CO_2	586	153 - 679	583	413 - 687	607	467 - 721	593	450 - 676
Nitrous Acid	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
Nitric Acid	<1.0	<1.0 – 1.4	<1.0	<1.0 – 1.2	<1.0	NA	<1.0	NA
HCN	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
CO	<1.0	<1.0 – 1.4	<1.0	<1.0 – 1.5	<1.0	<1.0 – 1.4	<1.0	<1.0 – 1.2
HCl	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
HF	<1.0	<1.0 – 1.2	<1.0	<1.0 – 1.0	<1.0	<1.0 – 1.0	<1.0	NA

NA - Not applicable.

Table 5.20. Concentrations [ppmv] of Selected Species in Off-Gas Measured by FTIR Spectroscopy while Processing the HLWS-09 Formulation.

Test	3A		3B		3C		3A-2		3D	
	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
N_2O	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
NO	5.8	2.1 – 20.8	6.9	<1.0 – 28.2	7.8	<1.0 – 30.2	8.6	1.1 – 32.2	6.0	<1.0 – 25.9
NO_2	<1.0	<1.0 – 1.7	<1.0	<1.0 – 1.6	<1.0	<1.0 – 1.4	<1.0	<1.0 – 1.8	<1.0	<1.0 – 1.6
NH_3	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
H_2O [%]	2.3	1.5 – 3.5	2.6	1.0 – 4.1	2.8	1.1 – 4.9	3.2	1.4 – 4.6	2.6	1.3 – 4.5
CO_2	955	531 - 2303	953	431 - 2507	944	422 - 2611	1146	479 - 3356	955	414 - 2598
Nitrous Acid	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
Nitric Acid	<1.0	NA	1.0	<1.0 – 1.8	1.4	<1.0 – 1.8	1.3	<1.0 – 4.0	<1.0	<1.0 – 1.0
HCN	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA	<1.0	NA
CO	<1.0	NA	<1.0	<1.0 – 2.1	<1.0	<1.0 – 1.1	<1.0	<1.0 – 1.0	<1.0	NA
HCl	<1.0	NA	<1.0	<1.0 – 1.0	<1.0	<1.0 – 1.1	<1.0	<1.0 – 3.3	<1.0	NA
HF	<1.0	NA	<1.0	<1.0 – 1.0	<1.0	<1.0 – 1.1	<1.0	<1.0 – 1.1	<1.0	NA

NA : Not applicable.

Table 5.20. Concentrations [ppmv] of Selected Species in Off-Gas Measured by FTIR Spectroscopy while Processing the HLWS-09 Formulation (Continued).

Test	**3E**	
	Avg.	Range
N_2O	<1.0	NA
NO	6.2	<1.0 – 35.4
NO_2	<1.0	<1.0 – 2.0
NH_3	<1.0	NA
H_2O [%]	2.2	1.1 – 3.9
CO_2	925	415 - 4126
Nitrous Acid	<1.0	NA
Nitric Acid	1.0	<1.0 – 1.8
HCN	<1.0	NA
CO	<1.0	NA
HCl	<1.0	<1.0 – 1.5
HF	<1.0	<1.0 – 1.1

Figure 1.1. DM10 melter and feed tank; off-gas system is in the background to the left.

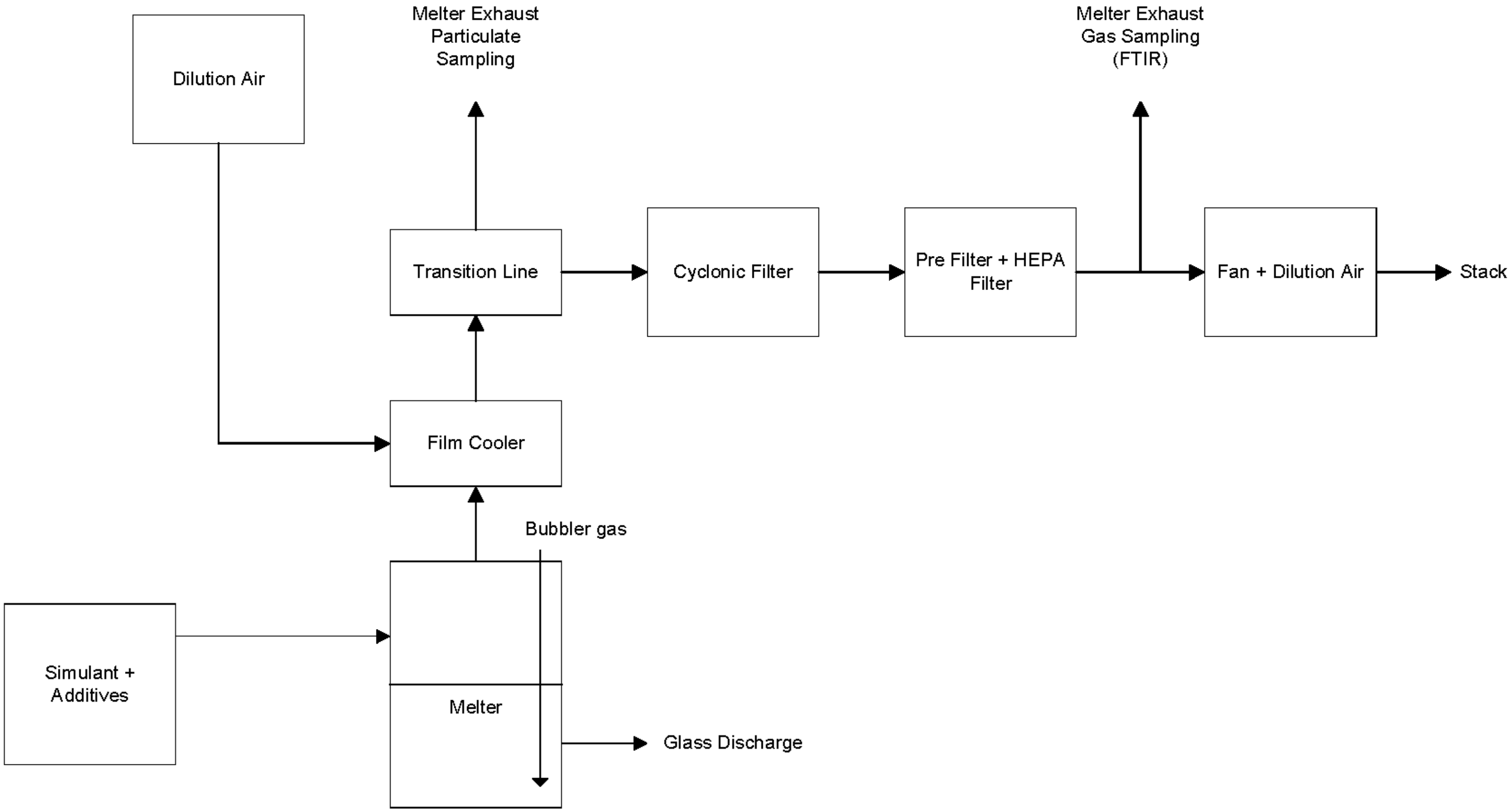


Figure 1.2. Schematic diagram of DM 10 vitrification system.

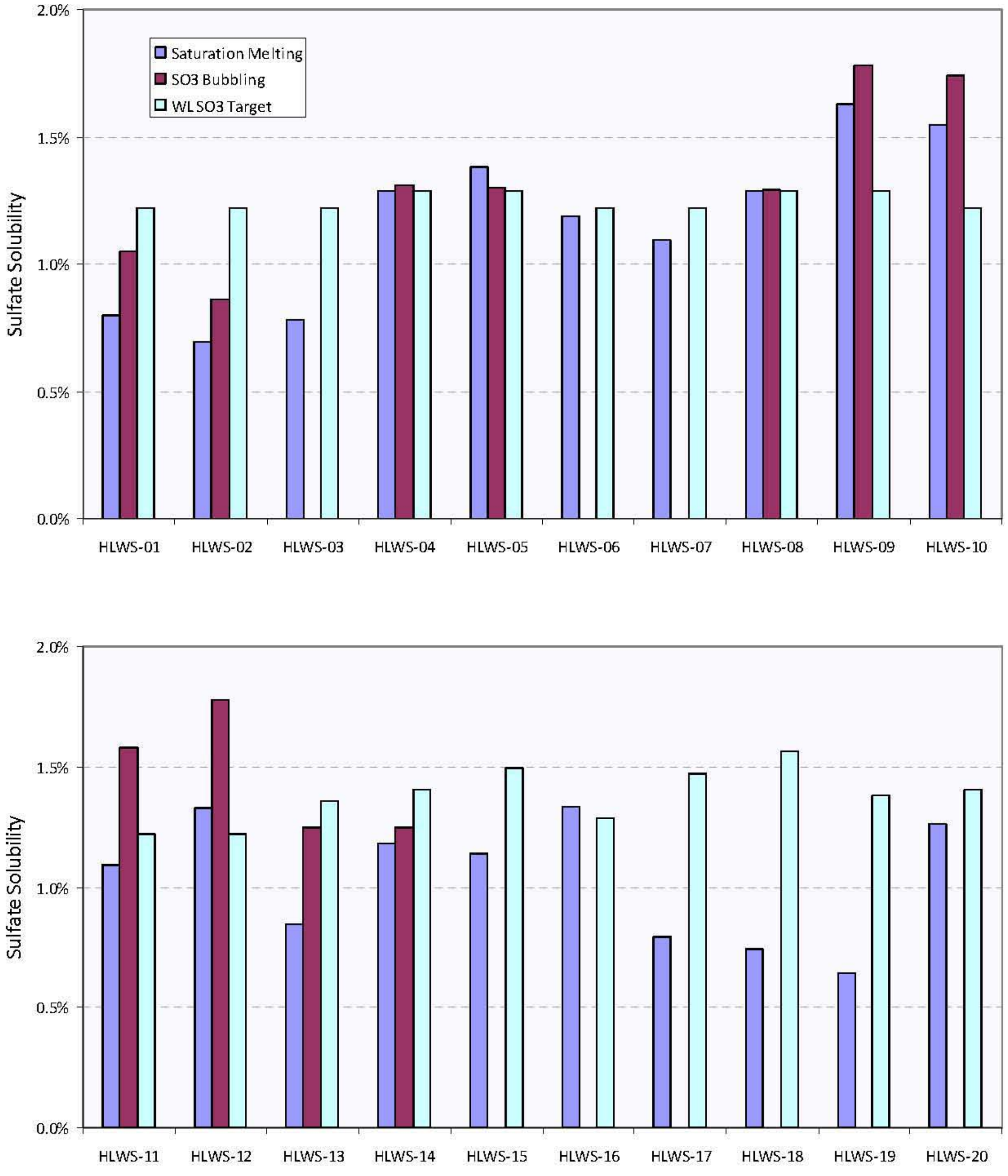
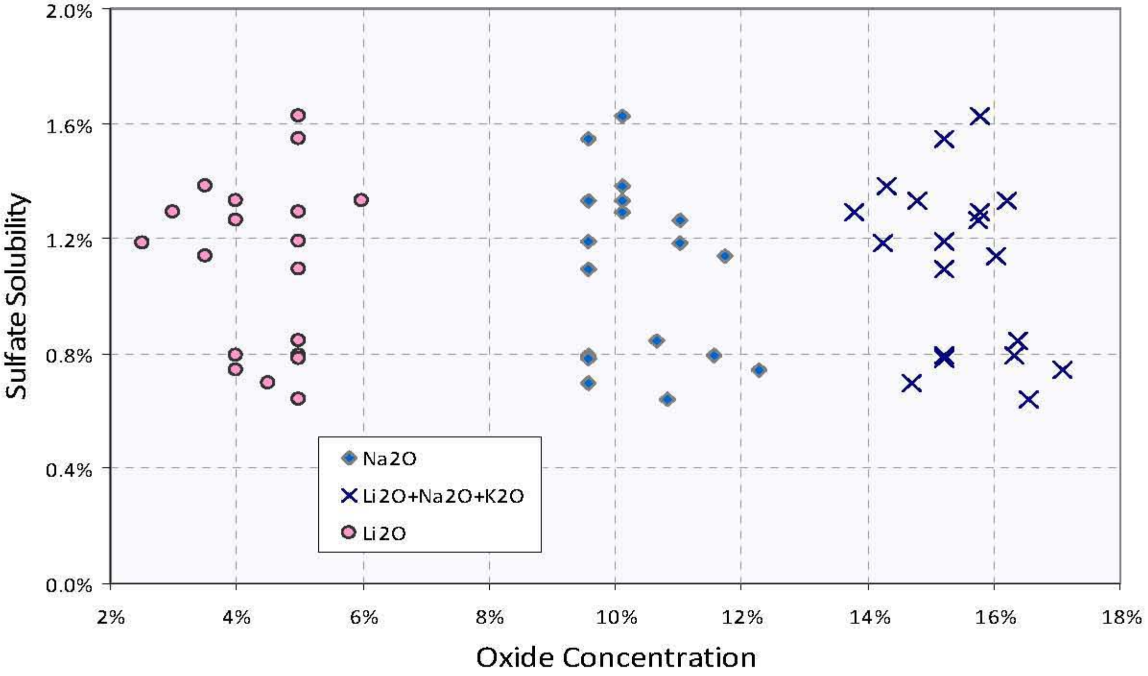


Figure 2.1. Comparison of sulfate solubilities (as wt% SO_3) measured for HLWS glasses with target SO_3 values.



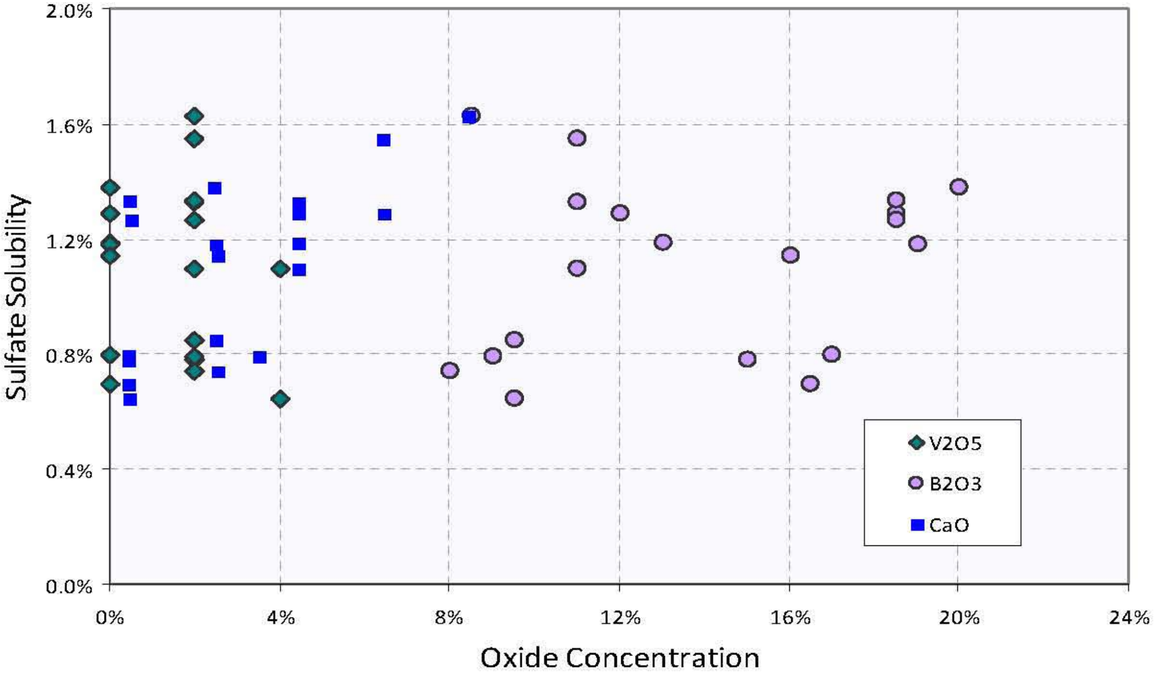


Figure 2.2. Sulfate solubility (as wt% SO_3) in HLWS glasses versus concentrations of selected oxides in glass.

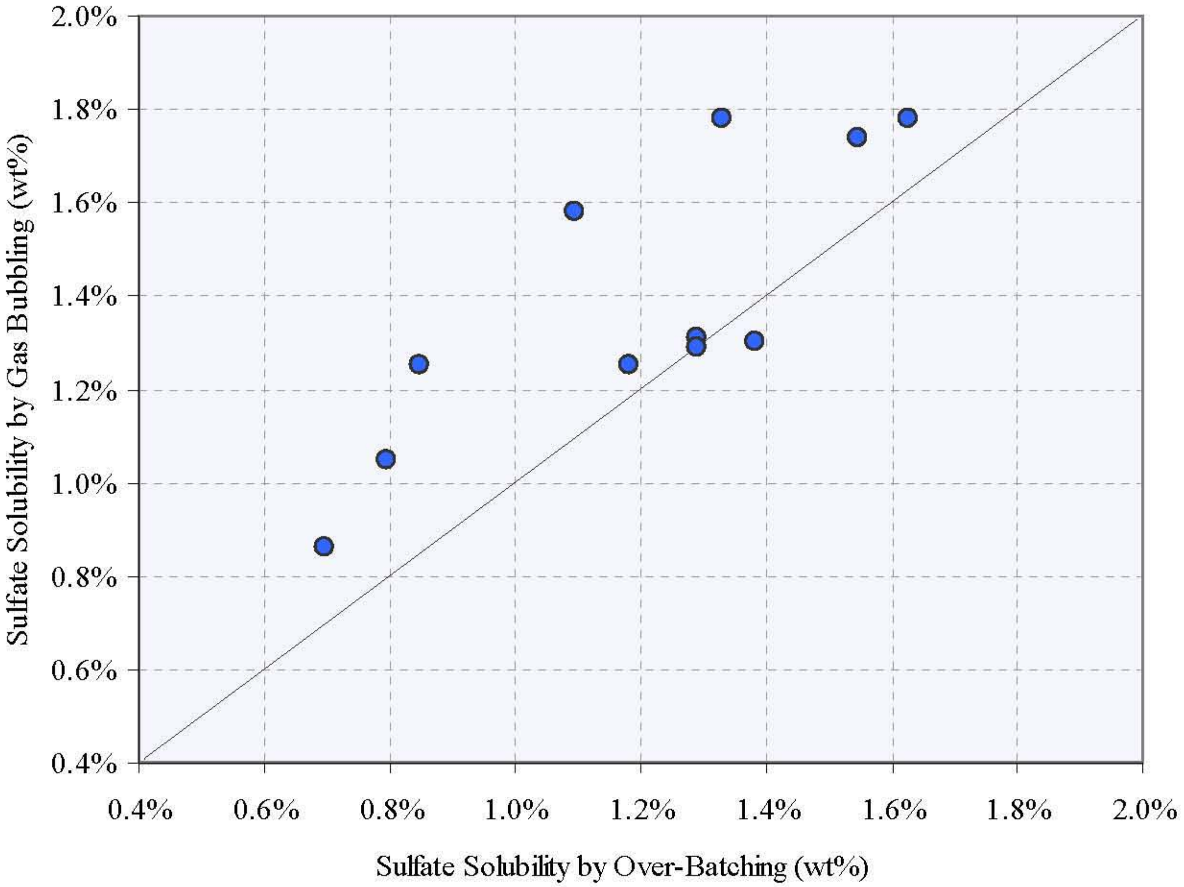
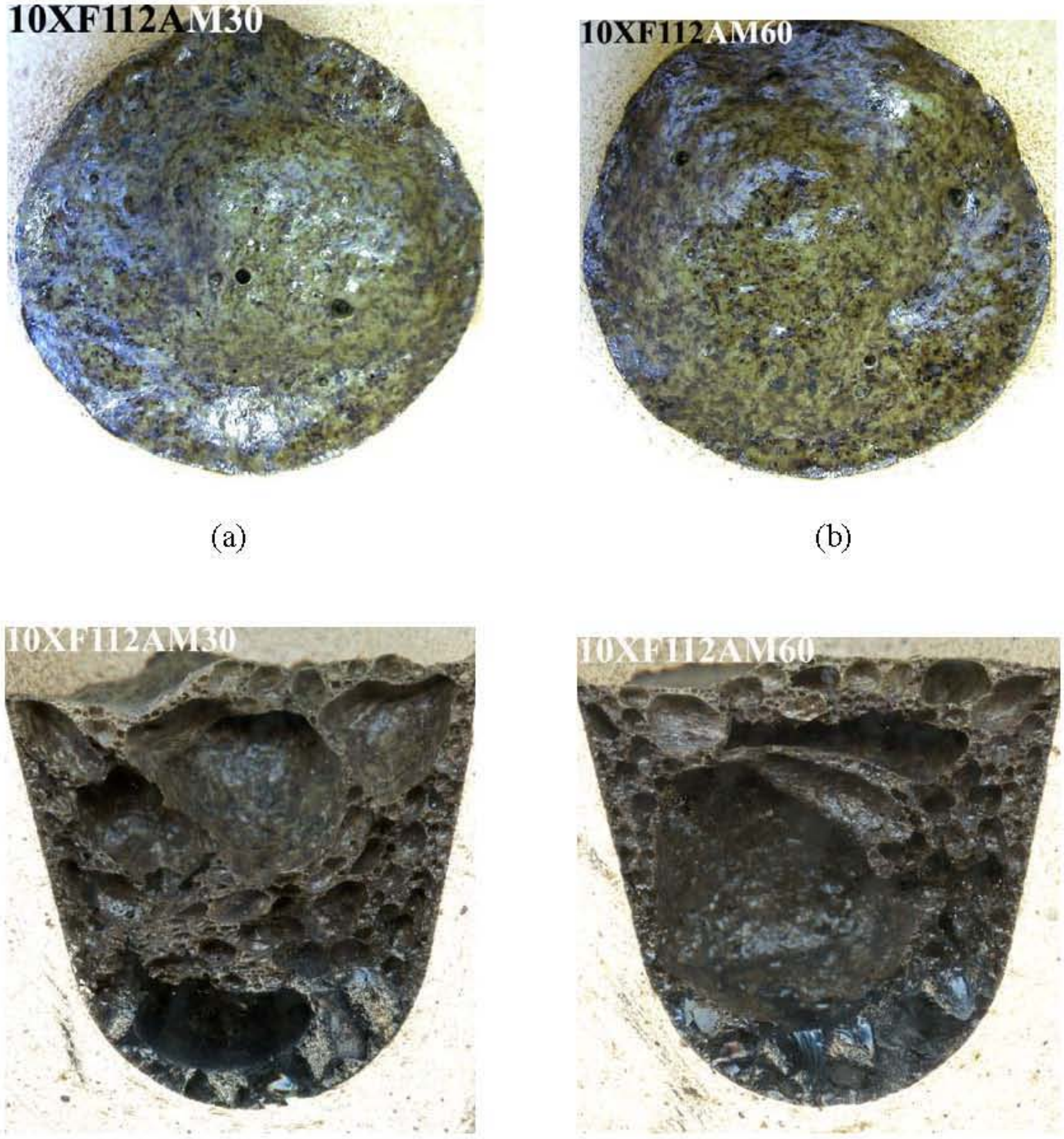


Figure 2.3. Sulfur solubility (as wt% SO_3) in HLWS glasses by batch saturation and gas bubbling.



(a) (b)

(c) (d)

Figure 2.4. Images of feed sample of HLWS-09 after Vertical Gradient Furnace tests: a) Top view of 30 minutes VGF test; b) Top view of 60 minutes VGF test; c) Cross sectional view of 30 minutes VGF test; d) Cross sectional view of 60 minutes VGF test.

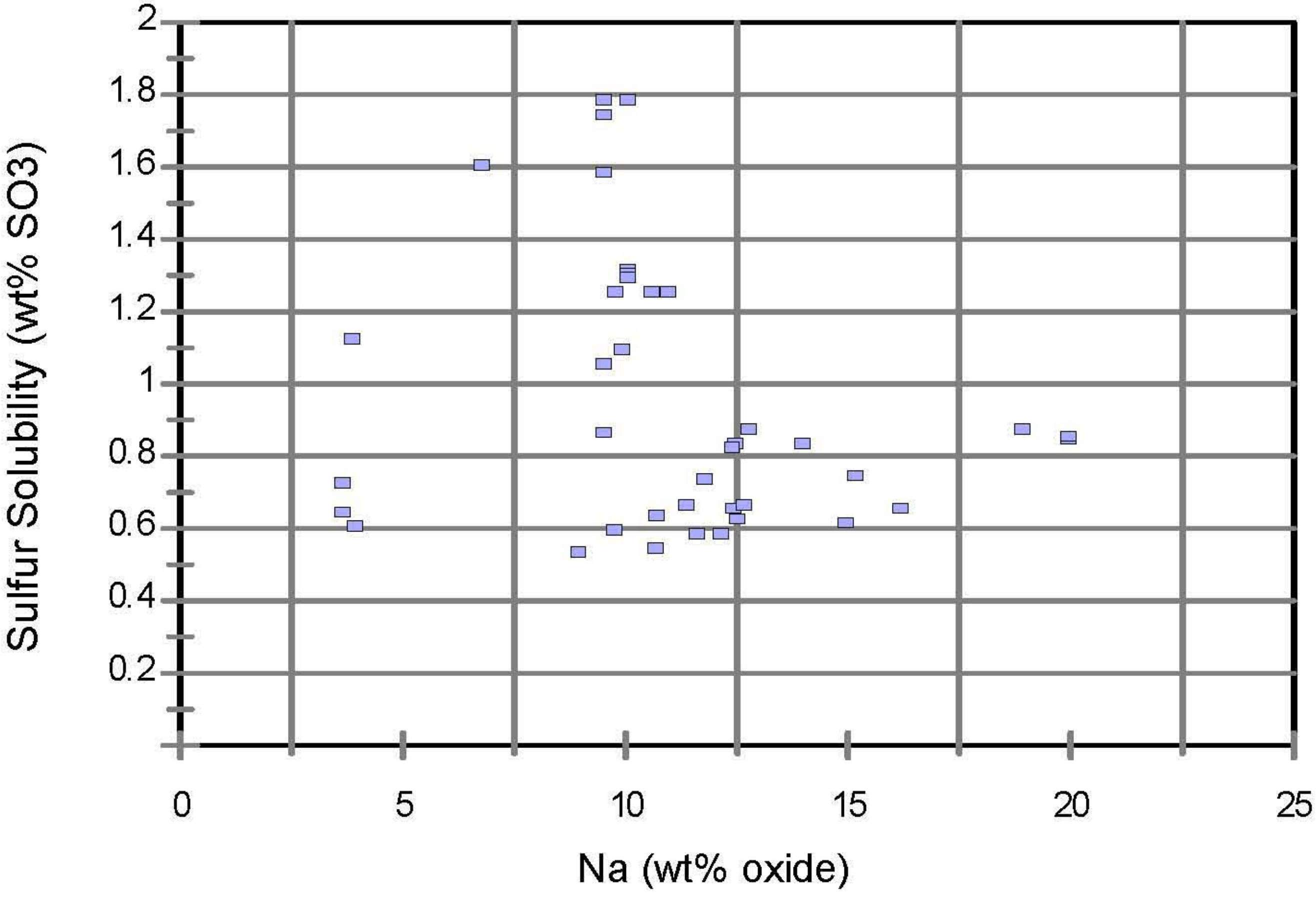


Figure 3.1. Measured sulfur solubility and sodium content for 39 HLW glass formulations.

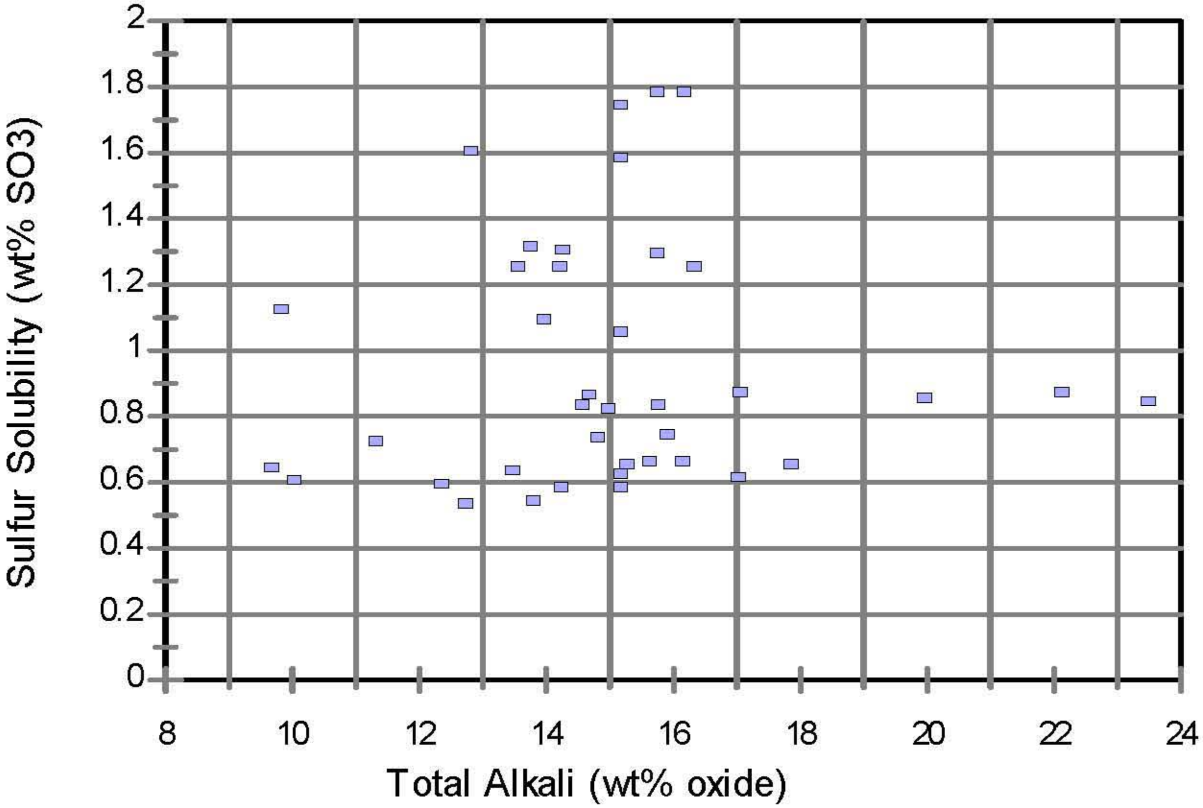


Figure 3.2. Measured sulfur solubility and alkali content for 39 HLW glass formulations.

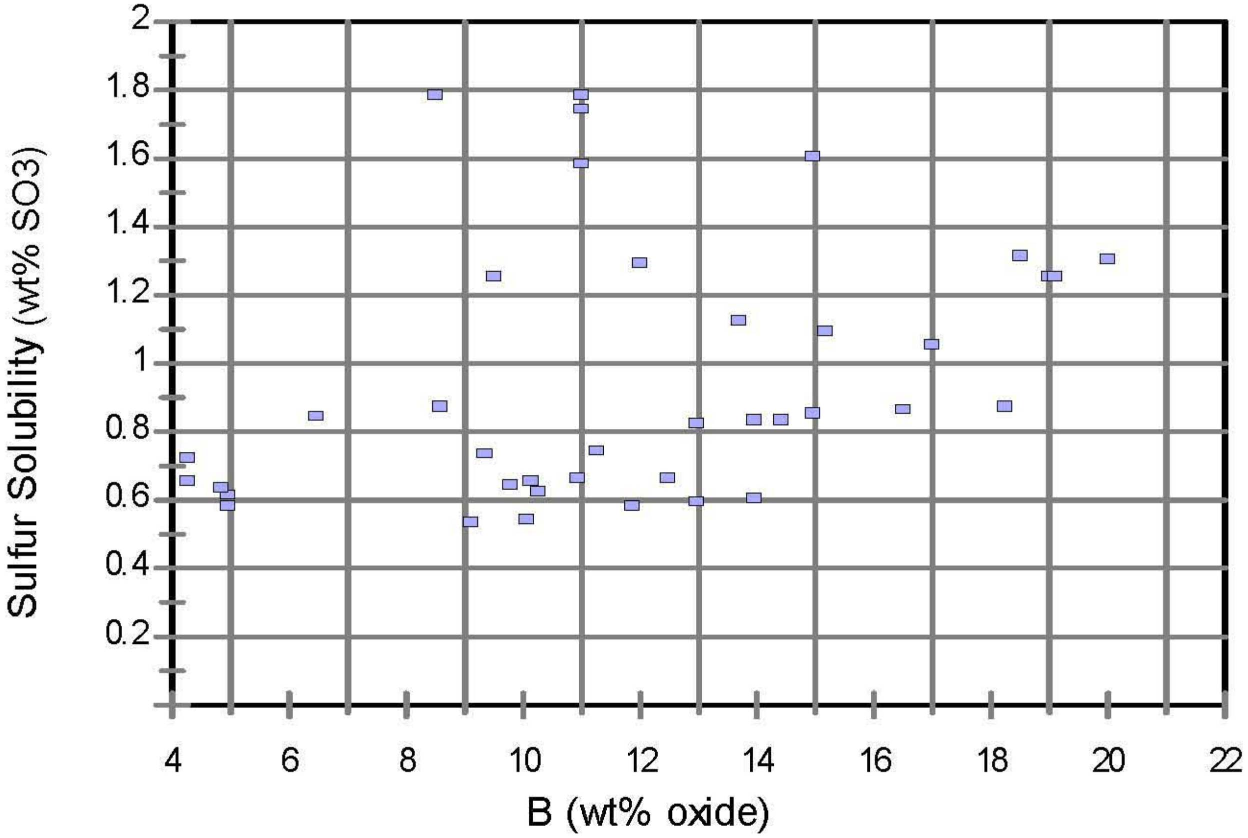


Figure 3.3. Measured sulfur solubility and boron content for 39 HLW glass formulations.

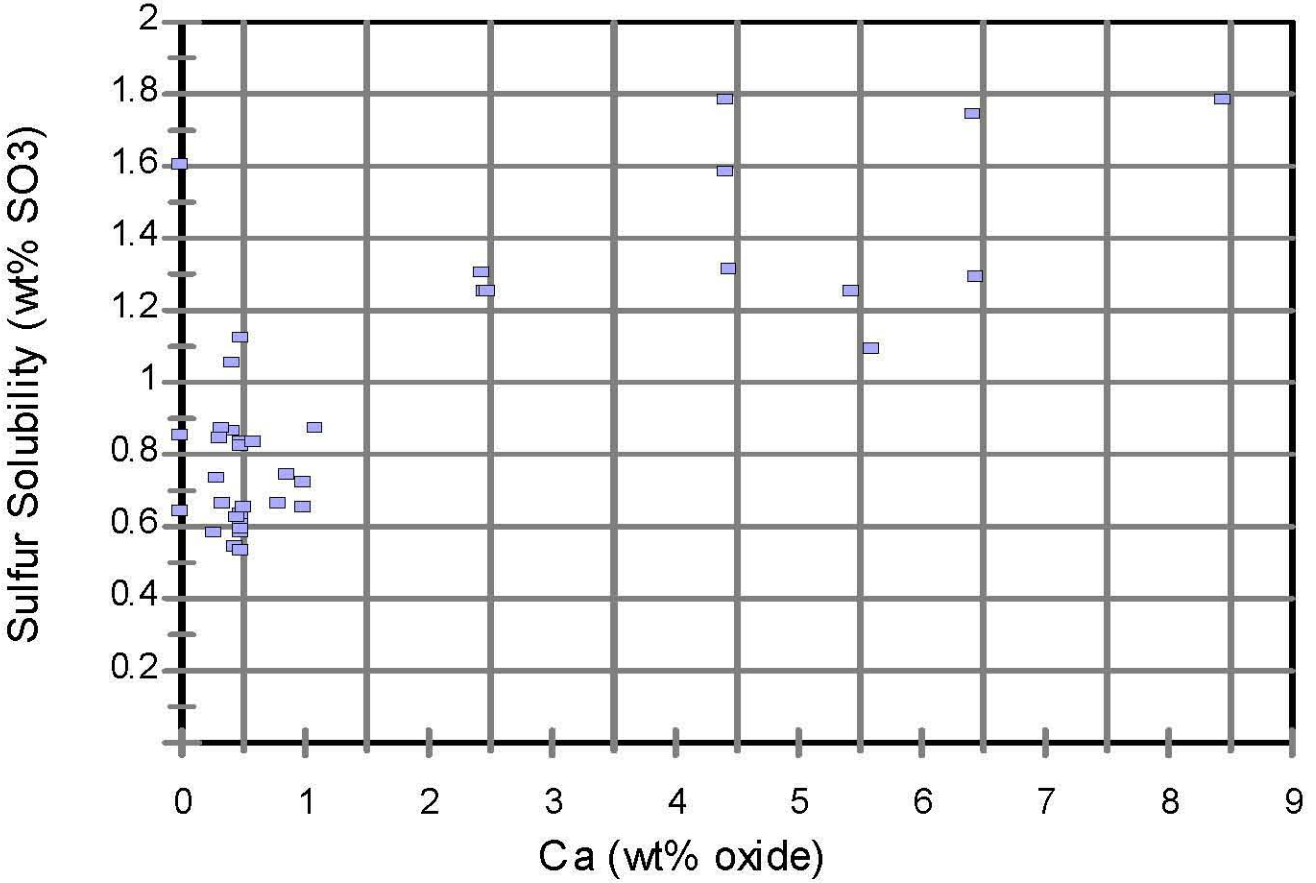


Figure 3.4. Measured sulfur solubility and calcium content for 39 HLW glass formulations.

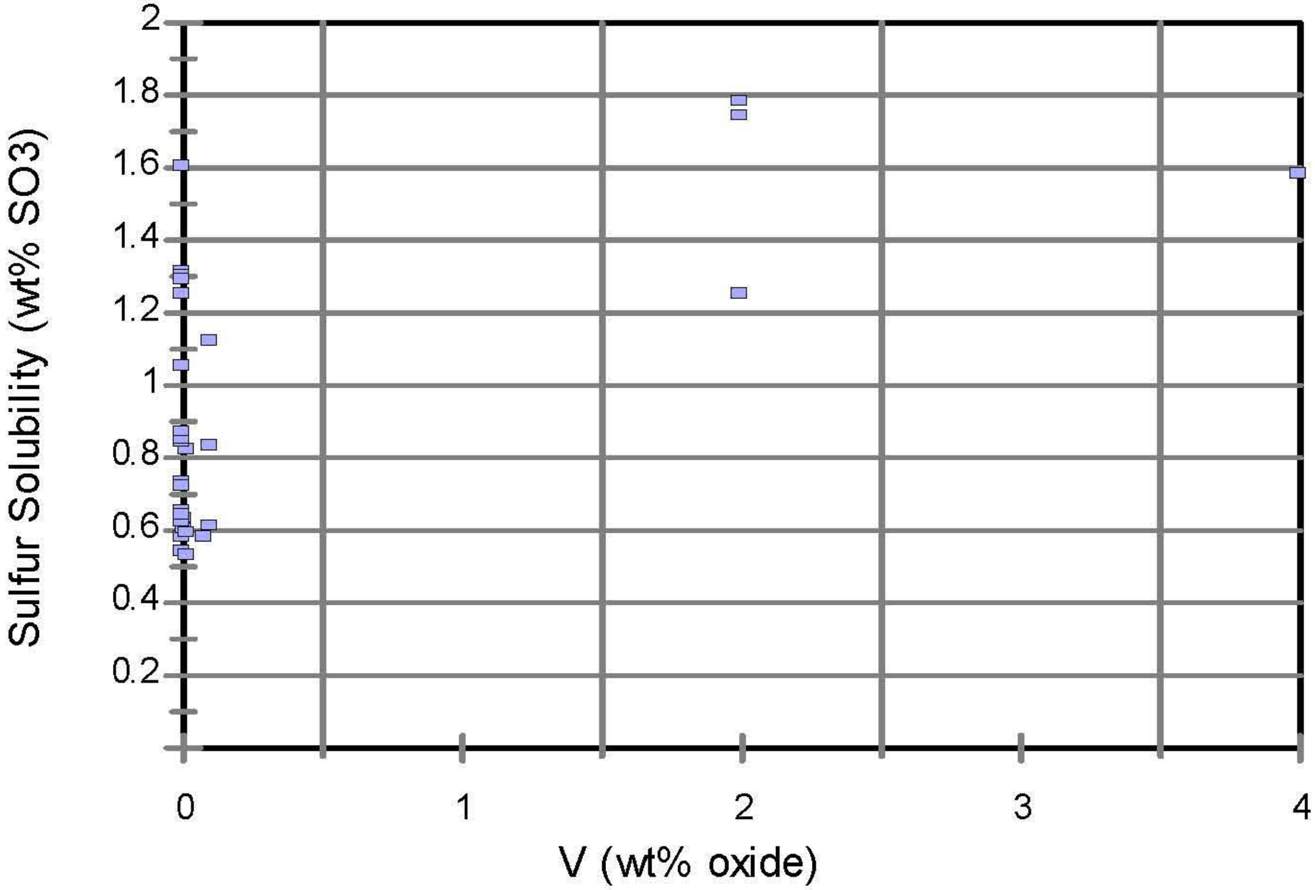


Figure 3.5. Measured sulfur solubility and vanadium content for 39 HLW glass formulations.

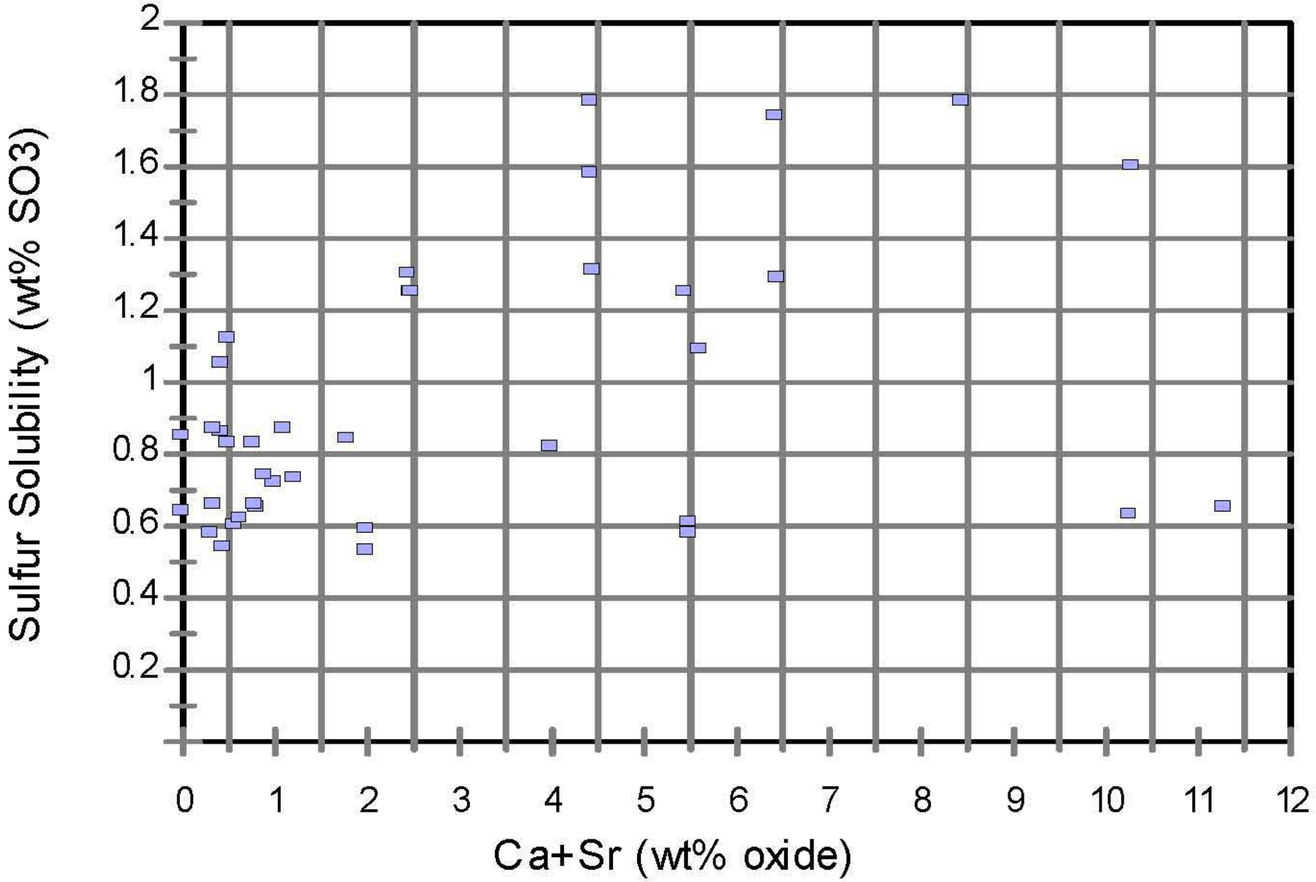


Figure 3.6. Measured sulfur solubility and calcium + strontium content for 39 HLW glass formulations.

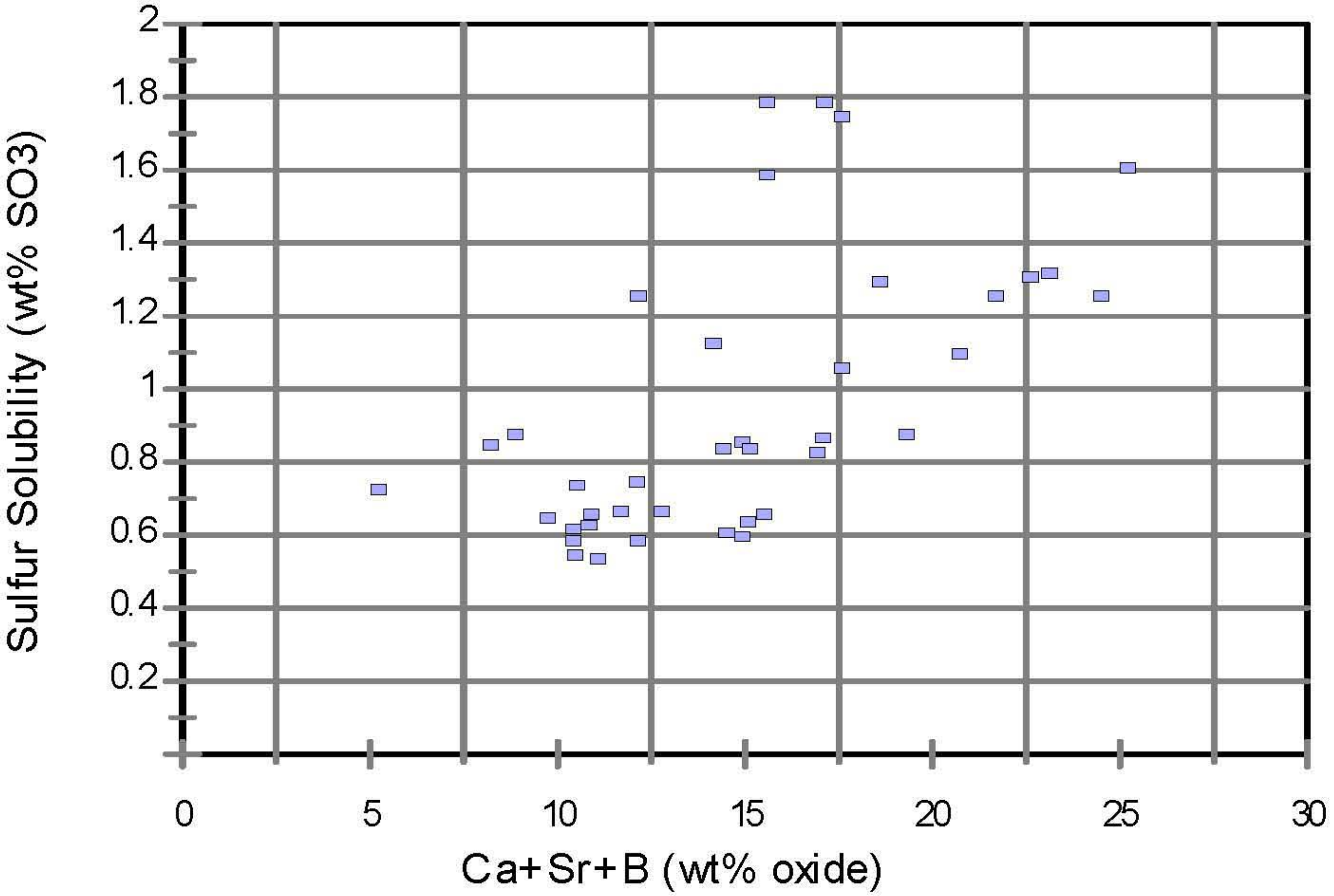


Figure 3.7. Measured sulfur solubility and calcium + strontium + boron content for 39 HLW glass formulations.

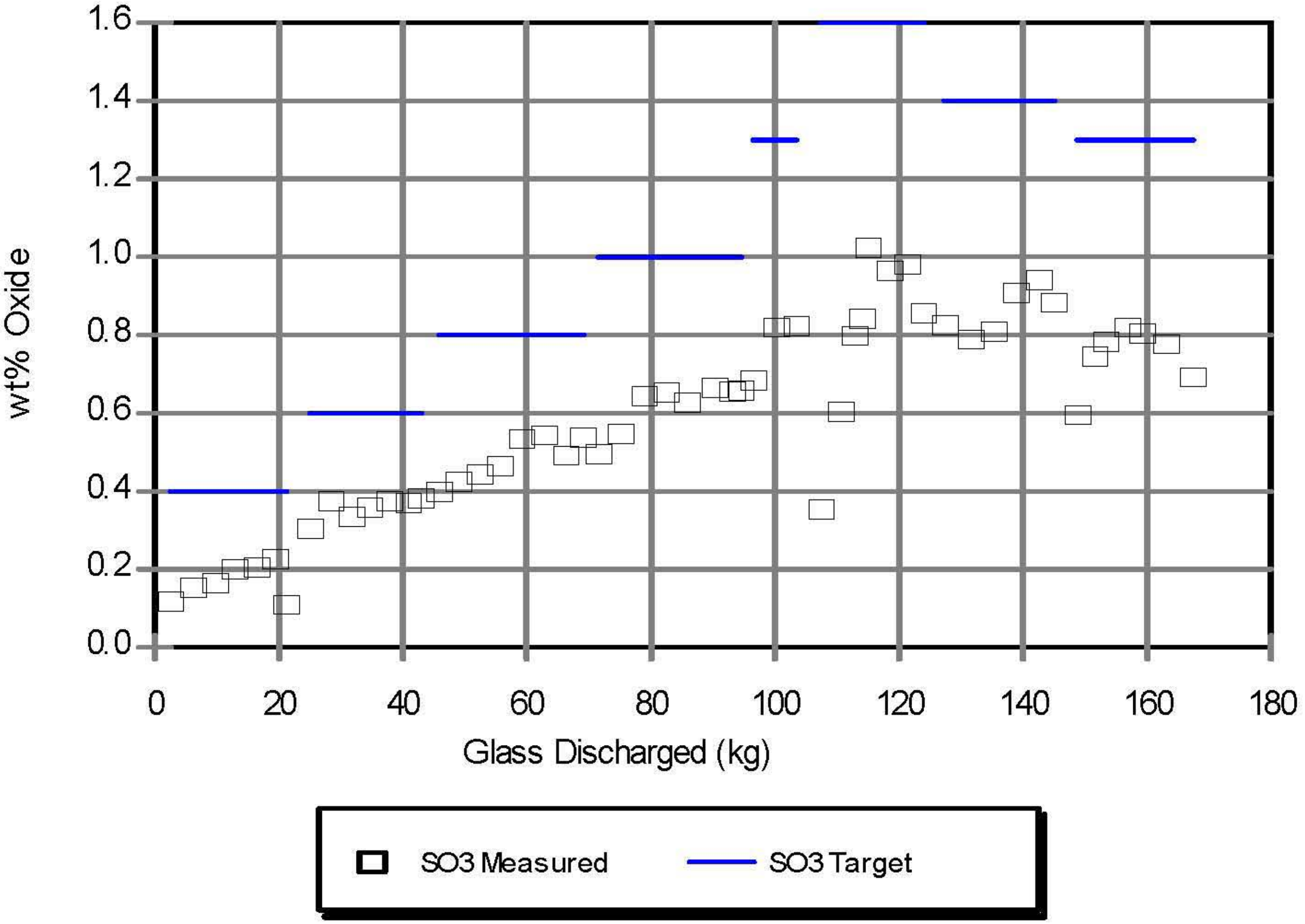


Figure 4.1. XRF measured product and target glass sulfur concentrations while processing the HWI-Al-19 glass formulation.

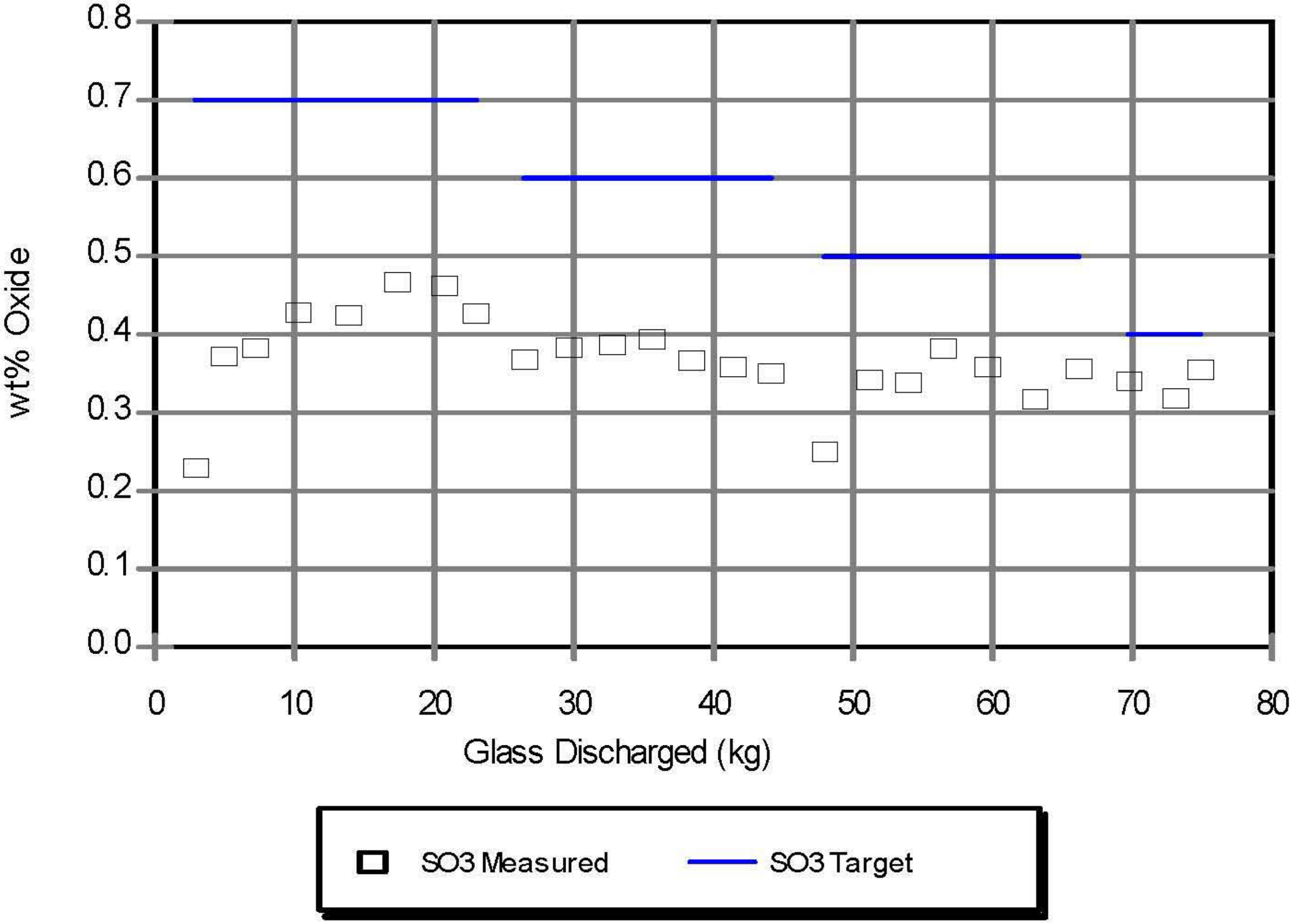


Figure 4.2. XRF measured product and target glass sulfur concentrations while processing the HLW-NG-Fe2 glass formulation.

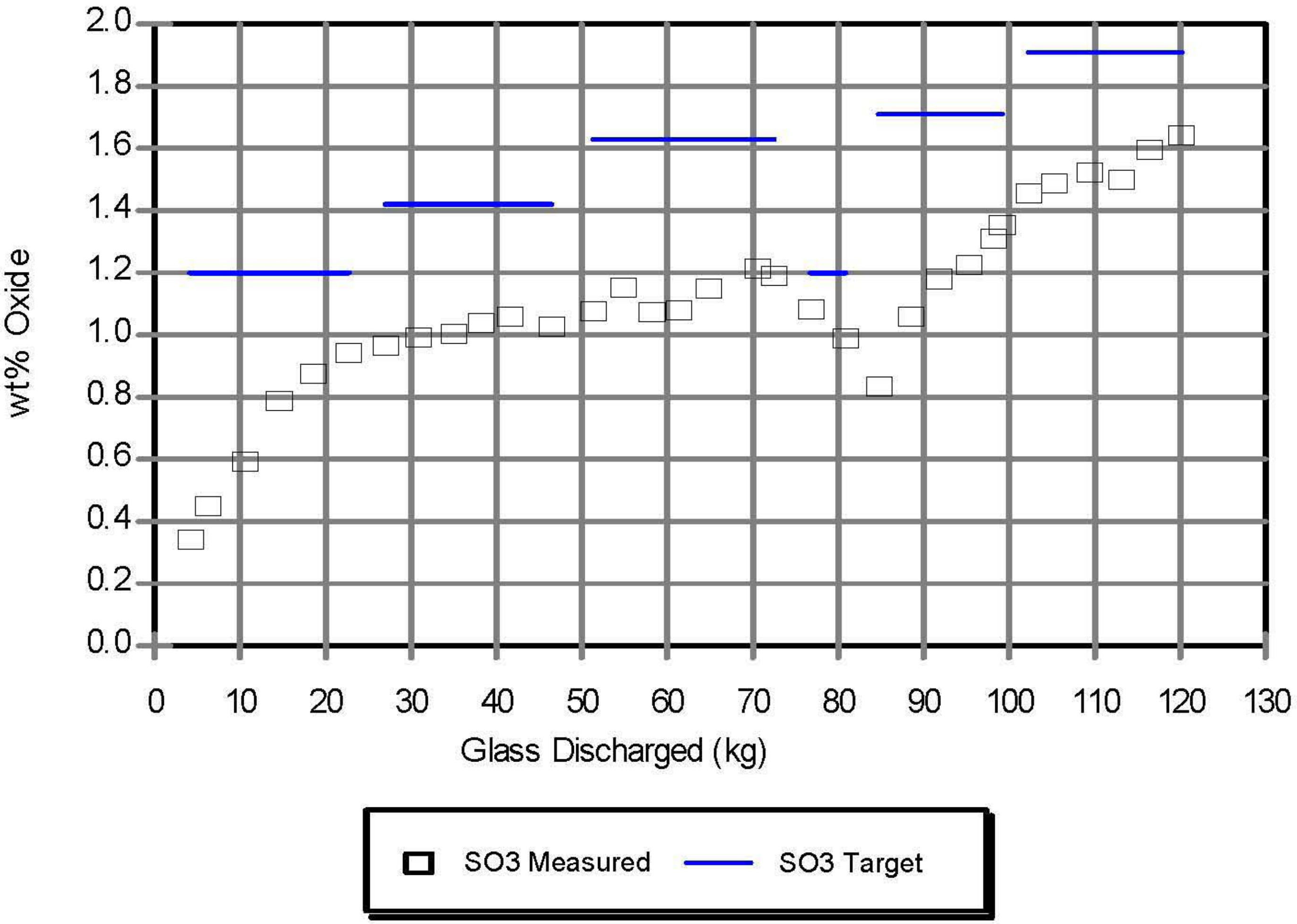


Figure 4.3. XRF measured product and target glass sulfur concentrations while processing the HLWS-09 glass formulation.

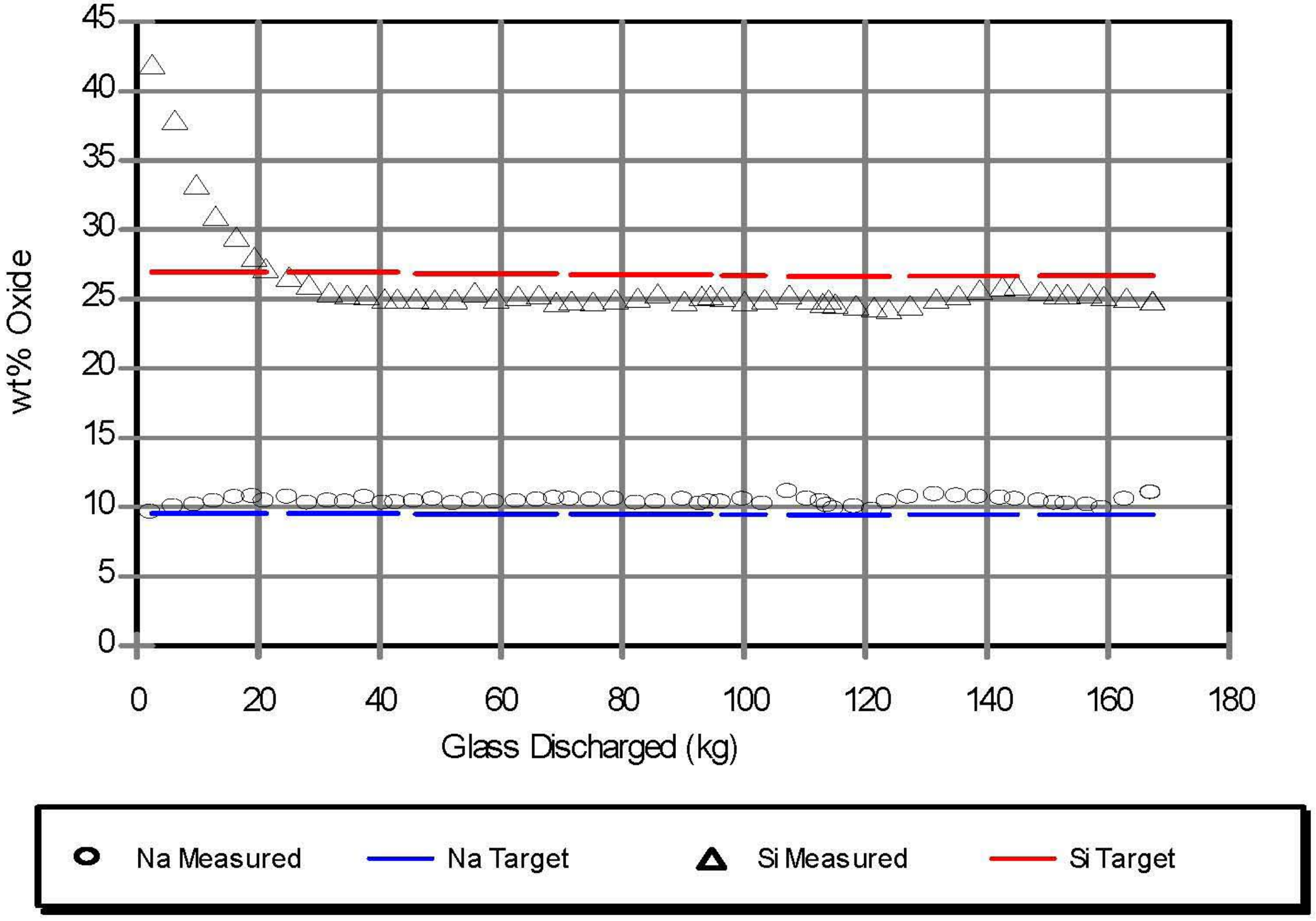


Figure 5.1. XRF measured product and target glass soda and silica concentrations while processing the HWI-Al-19 glass formulation.

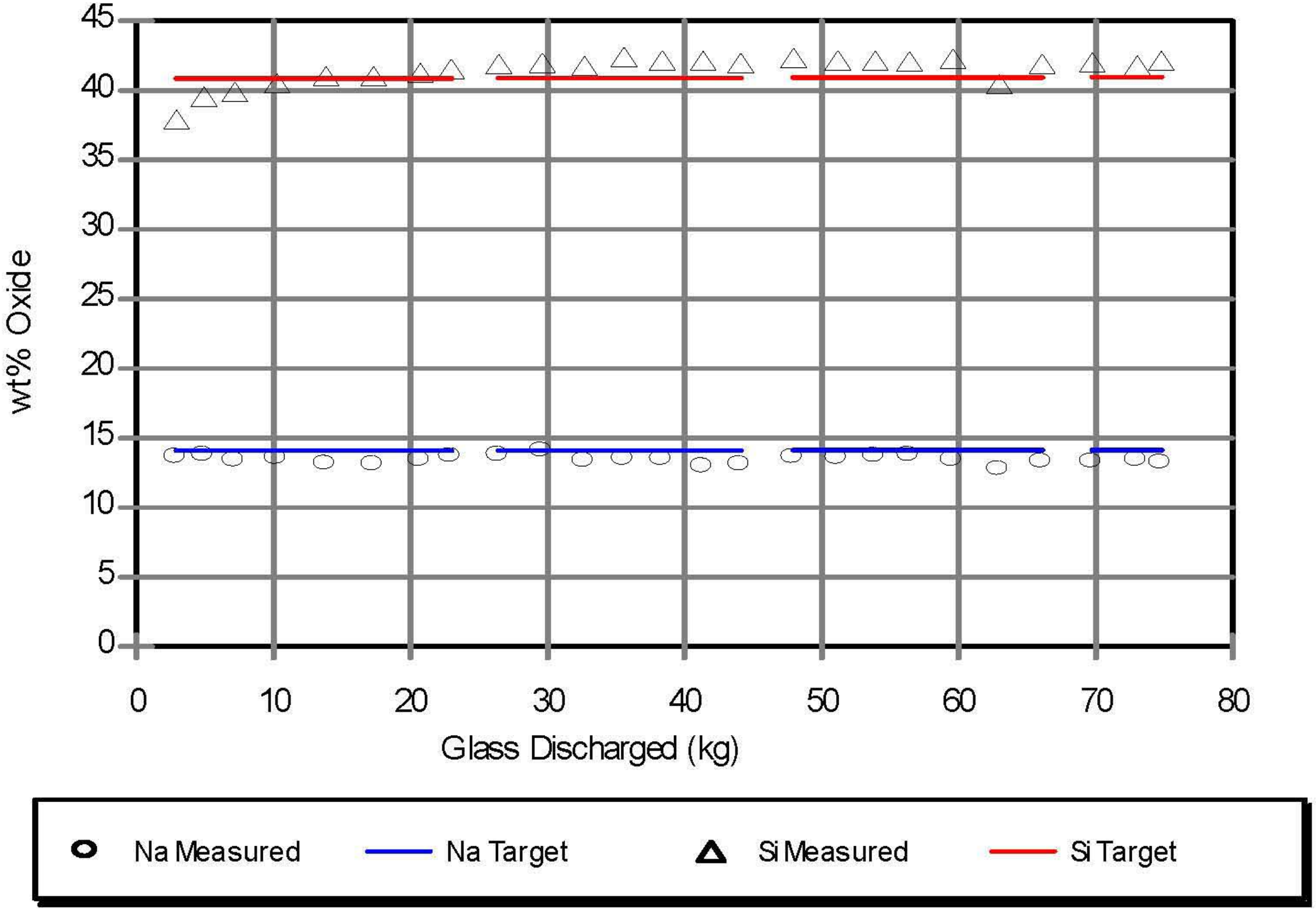


Figure 5.2. XRF measured product and target glass soda and silica concentrations while processing the HLW-NG-Fe2 glass formulation.

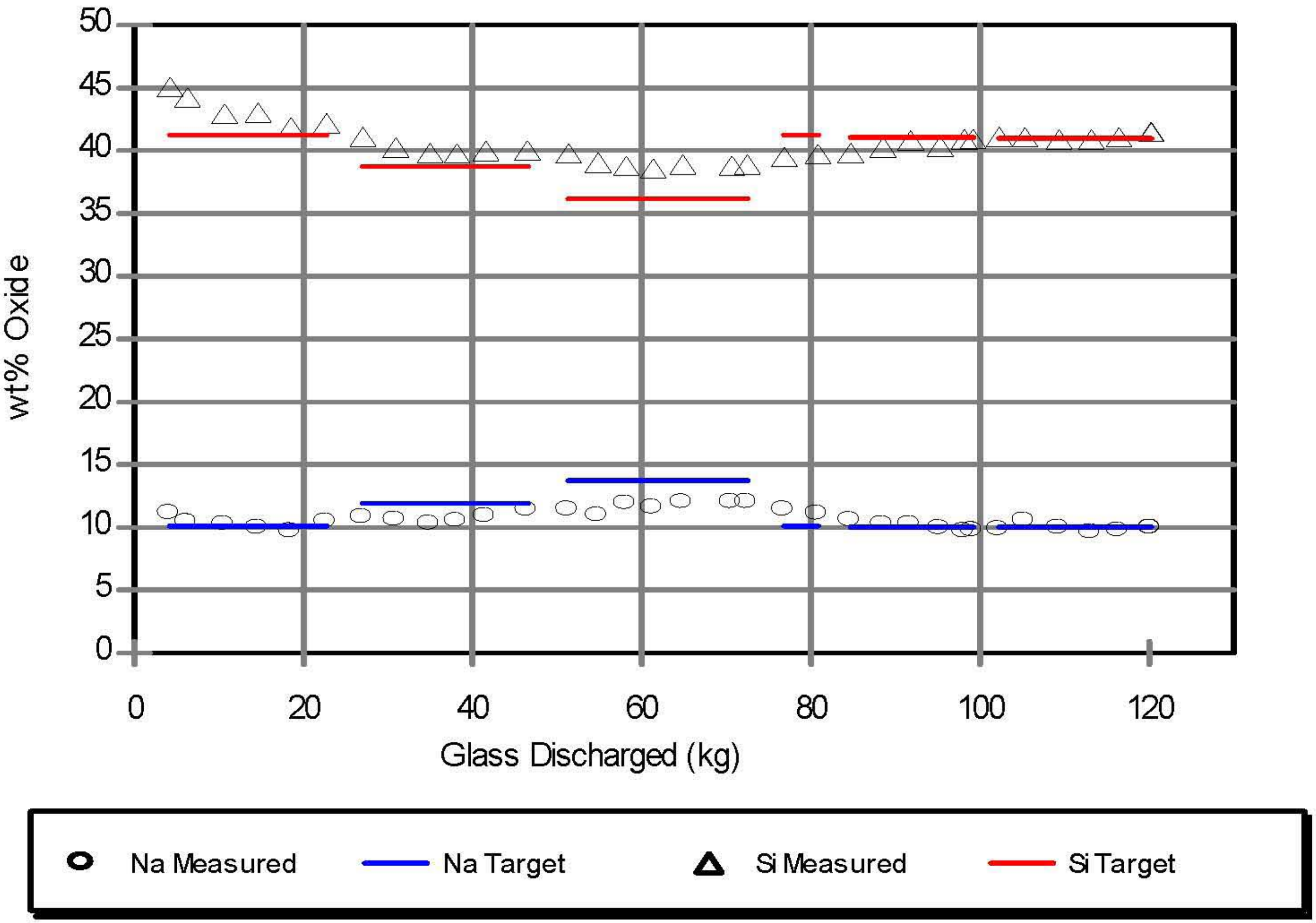


Figure 5.3. XRF measured product and target glass soda and silica concentrations while processing the HLWS-09 glass formulation.

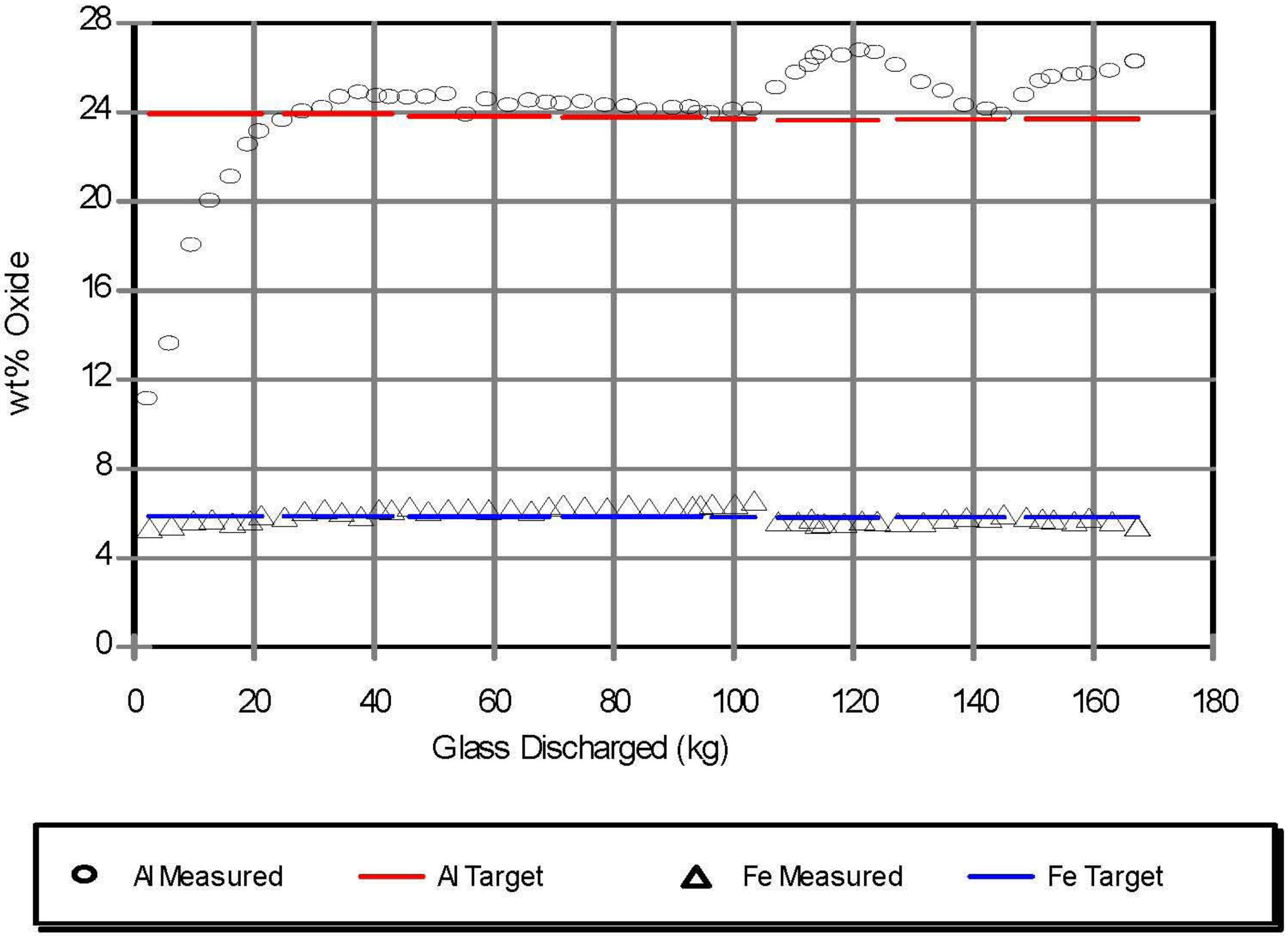


Figure 5.4. XRF measured product and target glass aluminum and iron oxide concentrations while processing the HWI-Al-19 glass formulation.

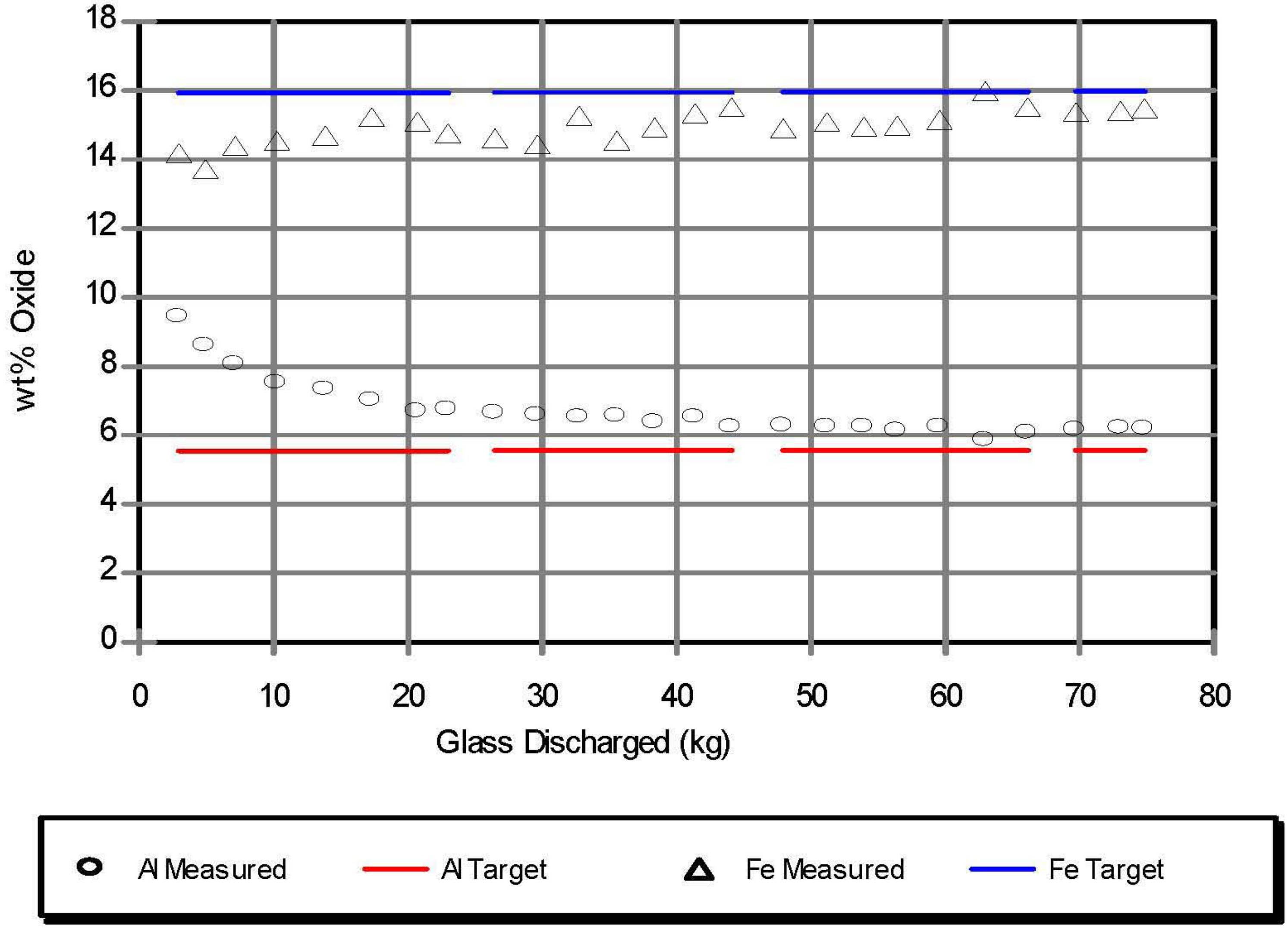


Figure 5.5. XRF measured product and target glass aluminum and iron oxide concentrations while processing the HLW-NG-Fe2 glass formulation.

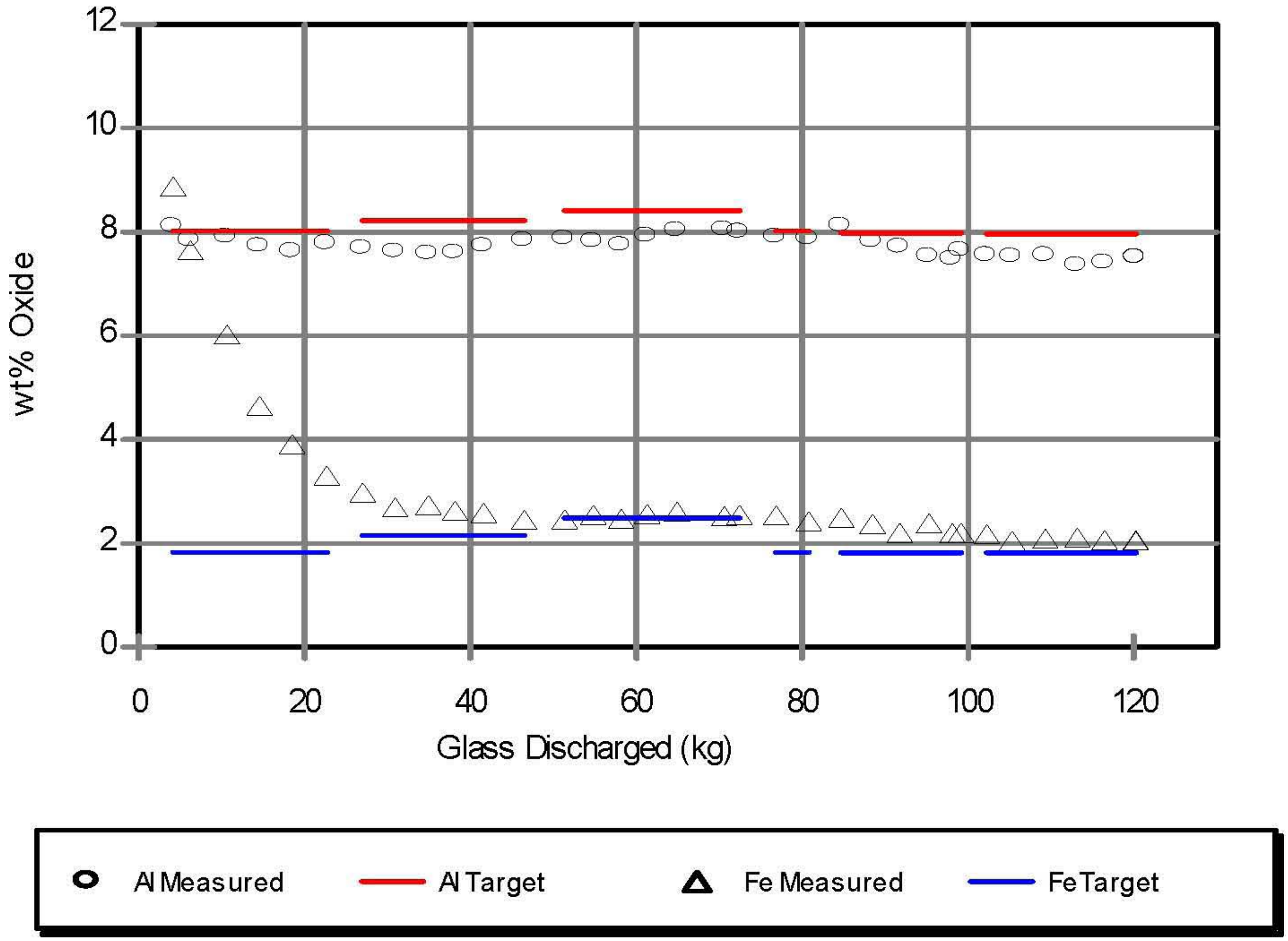


Figure 5.6. XRF measured product and target glass aluminum and iron oxide concentrations while processing the HLWS-09 glass formulation.

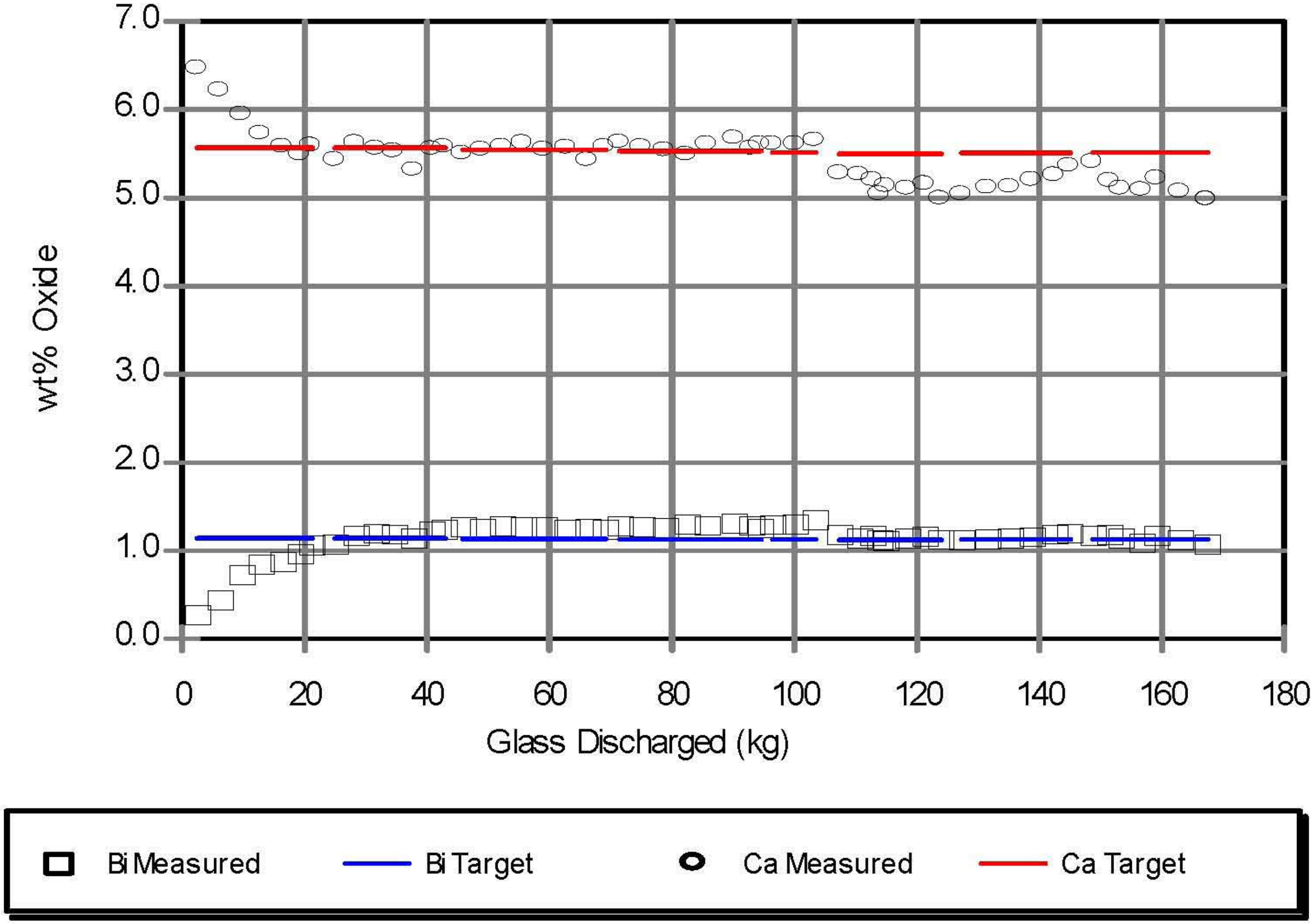


Figure 5.7. XRF measured product and target glass bismuth and calcium oxide concentrations while processing the HWI-Al-19 glass formulation.

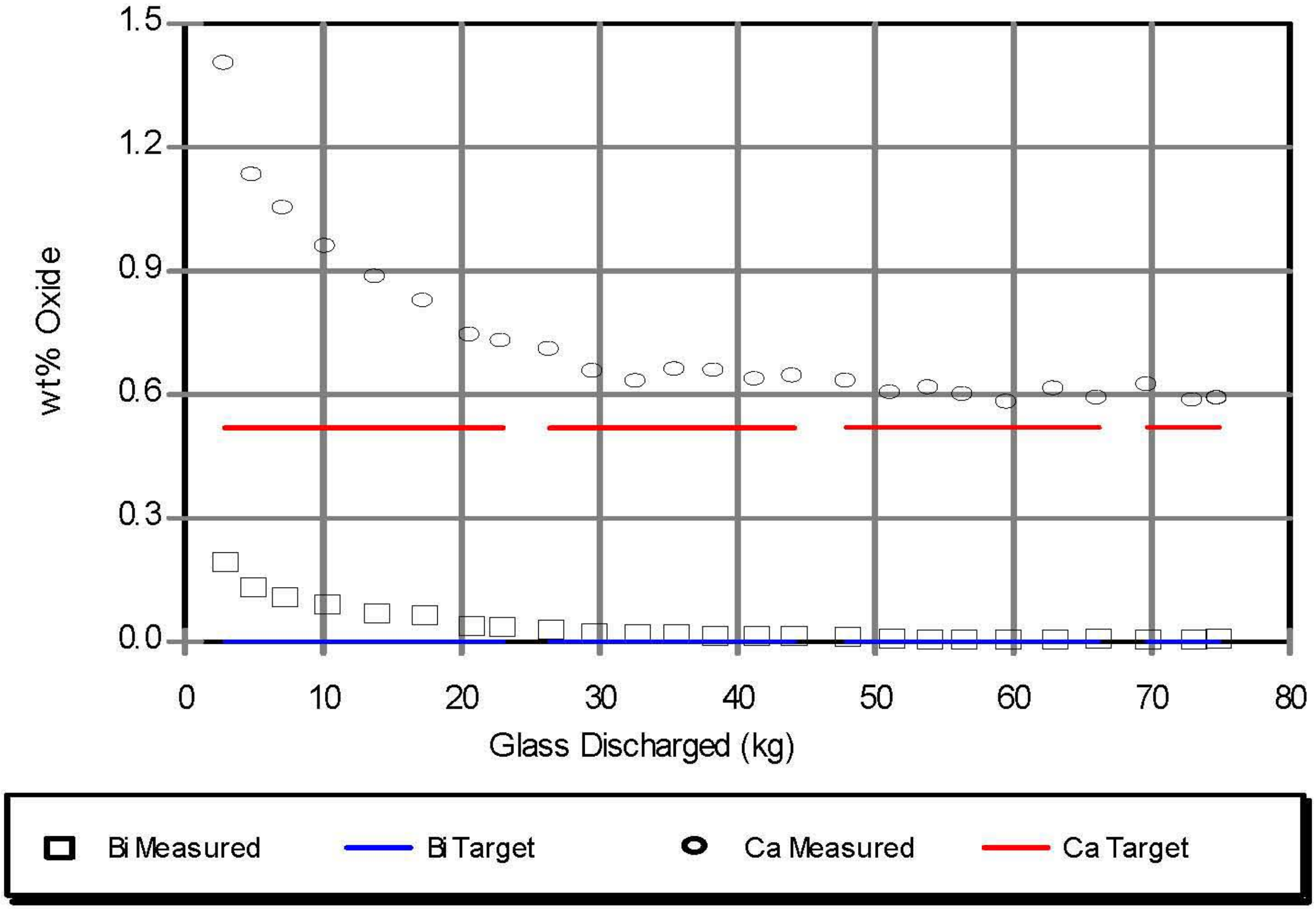


Figure 5.8. XRF measured product and target glass bismuth and calcium oxide concentrations while processing the HLW-NG-Fe2 glass formulation.

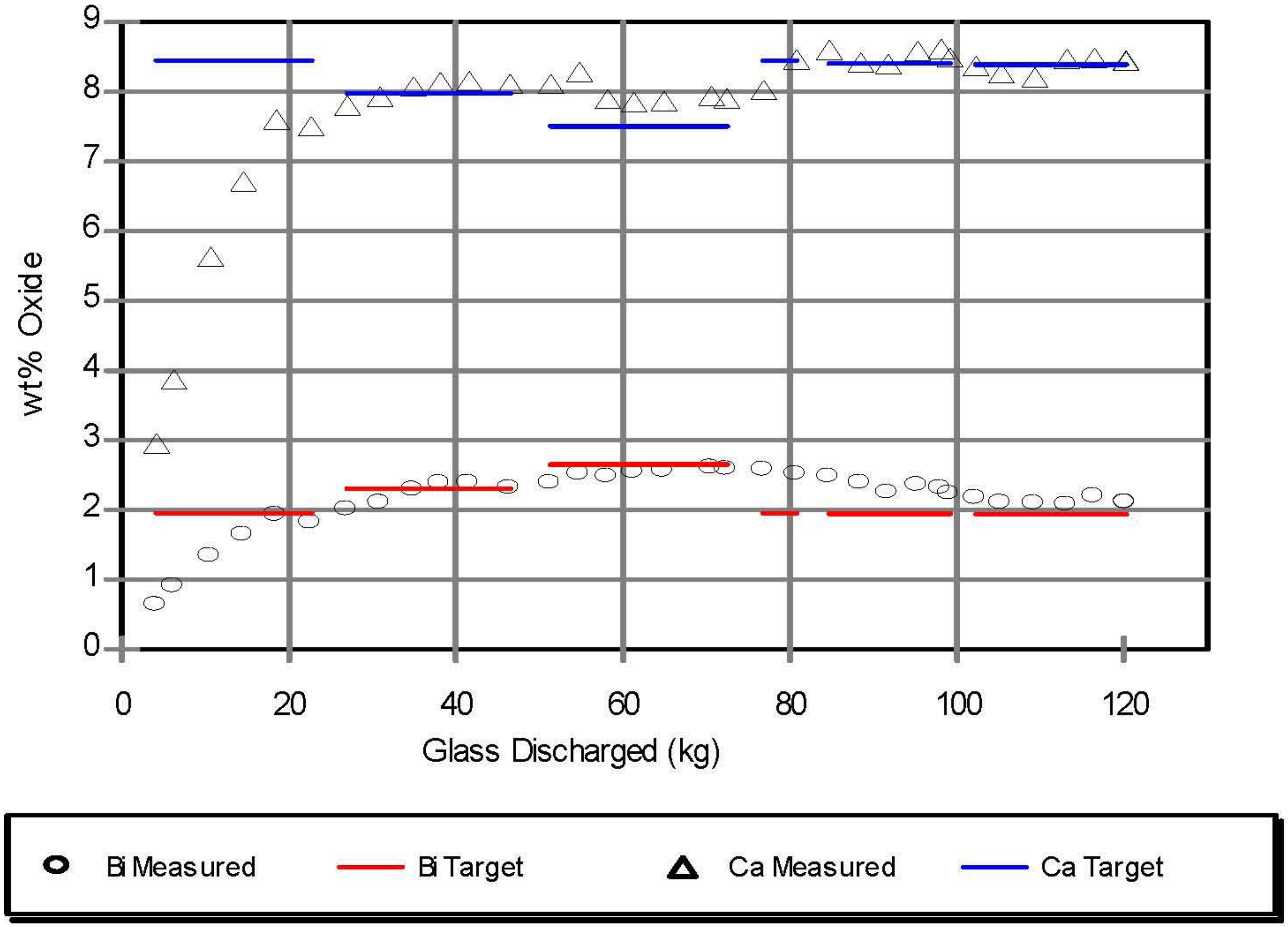


Figure 5.9. XRF measured product and target glass bismuth and calcium oxide concentrations while processing the HLWS-09 glass formulation.

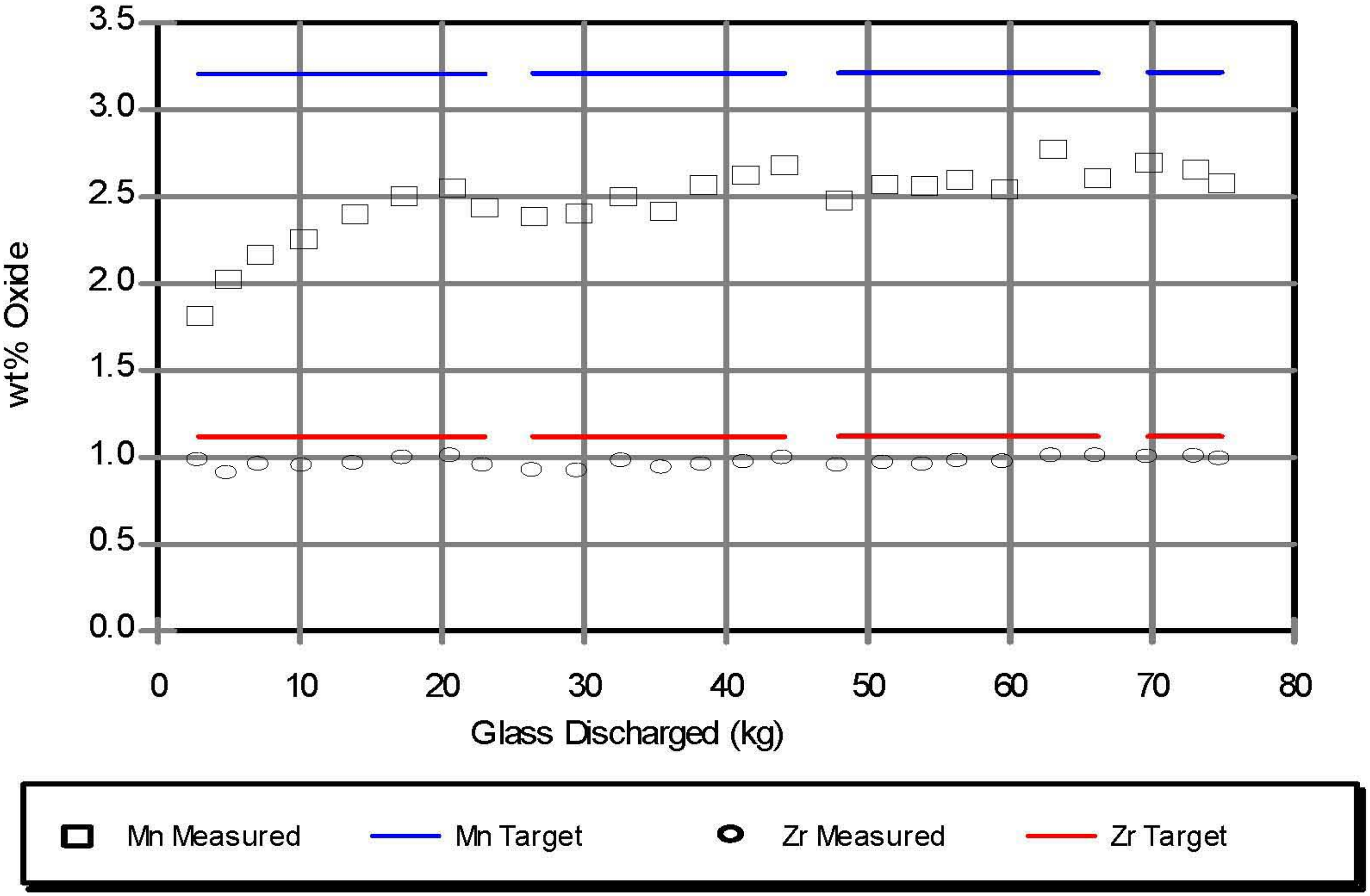


Figure 5.10. XRF measured product and target glass manganese and zirconium oxide concentrations while processing the HLW-NG-Fe2 glass formulation.

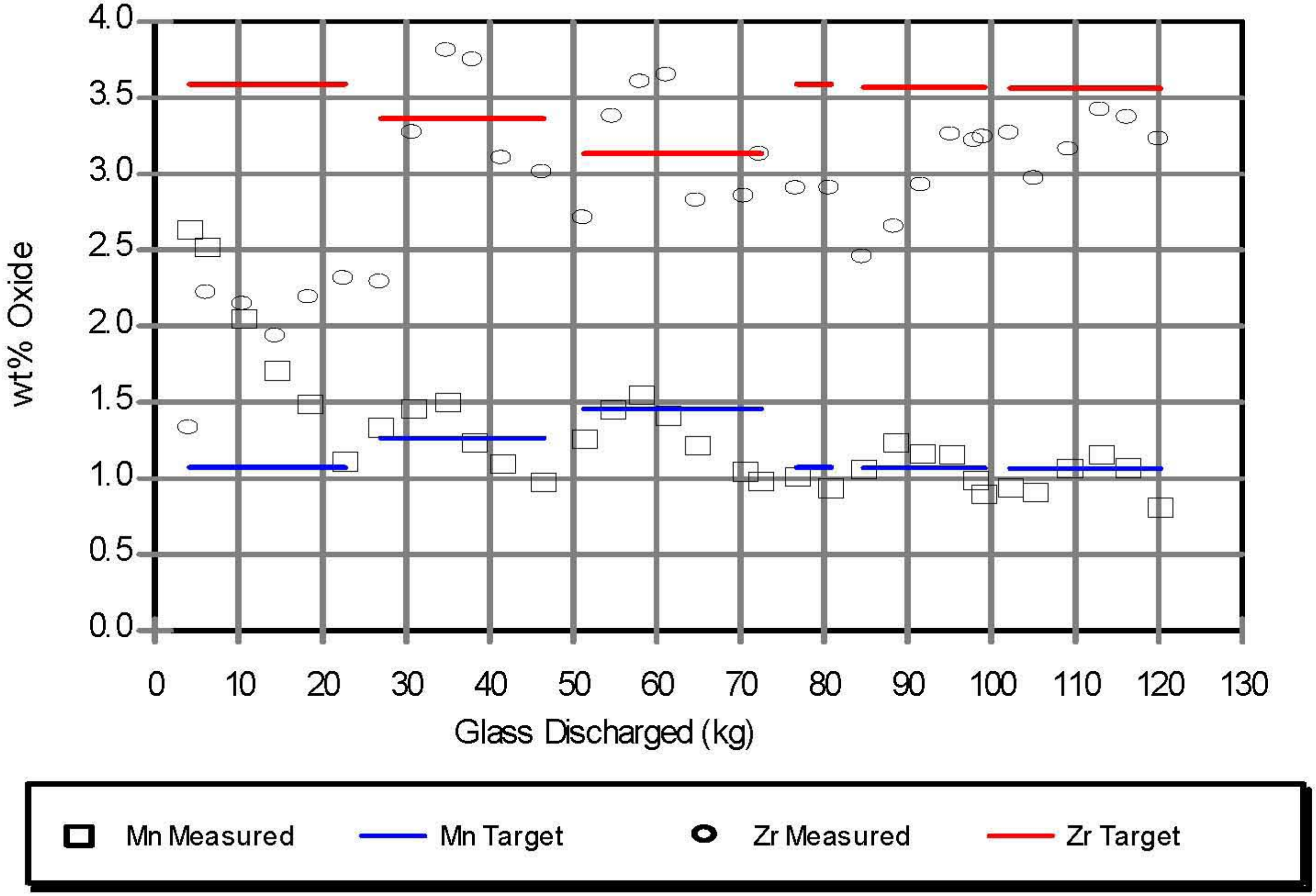


Figure 5.11. XRF measured product and target glass manganese and zirconium oxide concentrations while processing the HLWS-09 glass formulation.

Figure 5.12. Secondary phase observed on dip sample, 10W-D-40E, taken after Test 1F.

Figure 5.13. Secondary phase observed on dip sample, 10W-D-104C, taken after Test 2B.