Final Report - Glass Formulation Development and DM10 Melter Testing with ORP LAW Glasses, VSL-09R1510-2, Rev. 0, dated 6/12/09

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

**P.O. Box 450
Richland, Washington 99352**

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Assistant Secretary for Environmental Management

The logo for the Office of River Protection features a stylized, wavy grey shape above the text "Office of River Protection" in a bold, black, sans-serif font.

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Final Report

**Glass Formulation Development and DM10 Melter Testing
with ORP LAW Glasses**

prepared by

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and

**Department of Energy
Office of River Protection**

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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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List of Abbreviations

AA	Atomic Absorption Spectroscopy
ANL-LRM	Argonne National Laboratory – Low-Activity Waste Reference Material
CCC	Canister Centerline Cooling
CUA	Catholic University of America
DCP-AES	Direct Current Plasma - Atomic Emission Spectroscopy
DM	DuraMelter
DOE	Department of Energy
EDS	Energy Dispersive X-ray Spectroscopy
FTIR	Fourier Transform Infrared Spectroscopy
GFC	Glass Forming Chemical
HEPA	High-Efficiency Particulate Air Filter
HLW	High Level Waste
IC	Ion Chromatography
IHLW	Immobilized High Level Waste
ILAW	Immobilized Low Activity Waste
LAW	Low Activity Waste
M	Molarity
NQA	Nuclear Quality Assurance
ORP	Office of River Protection
PCT	Product Consistency Test
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
RPP	River Protection Project
SEM	Scanning Electron Microscope
SOP	Standard Operating Procedure
TFCOUP	Tank Farm Contractor Operation and Utilization Plan
VHT	Vapor Hydration Test
VSL	Vitreous State Laboratory
WTP	Hanford Tank Waste Treatment and Immobilization Plant
XRF	X-Ray Fluorescence Spectroscopy

SECTION 1.0 INTRODUCTION

About 50 million gallons of high-level mixed waste is currently stored in underground tanks at The United States Department of Energy's (DOE's) Hanford site in the State of Washington. The Hanford Tank Waste Treatment and Immobilization Plant (WTP) will provide DOE's Office of River Protection (ORP) with a means of treating this waste by vitrification for subsequent disposal. The tank waste will be separated into low- and high-activity waste fractions, which will then be vitrified respectively into Immobilized Low Activity Waste (ILAW) and Immobilized High Level Waste (IHLW) products. The ILAW product will be disposed in an engineered facility on the Hanford site while the IHLW product will be directed to the national deep geological disposal facility for high-level nuclear waste. The ILAW and IHLW products must meet a variety of requirements with respect to protection of the environment before they can be accepted for disposal.

The Office of River Protection is currently examining options to optimize the Low Activity Waste (LAW) Facility and LAW glass waste form. One option under evaluation is to enhance the waste processing rate of the vitrification plant currently under construction. It is likely that the capacity of the LAW vitrification plant can be increased incrementally by implementation of a variety of low-risk, high-probability changes, either separately or in combination. These changes include:

- Operating at the higher processing rates demonstrated at the LAW pilot melter
- Increasing the glass pool surface area within the existing external melter envelope
- Increasing plant availability
- Increasing the glass waste loading
- Operating the melter at a slightly higher temperature

The Vitreous State Laboratory (VSL) at The Catholic University of America (CUA) and EnergySolutions, Inc. have evaluated several of these potential incremental improvements for ORP in support of its evaluation of WTP LAW facility optimization [1]. Some of these incremental improvements have been tested at VSL including increasing the waste loading, increasing the processing temperature, and increasing the fraction of the sulfur in the feed that is partitioned to the off-gas stream (assuming that the present WTP recycle loop can be broken) [2-4]. These approaches successfully demonstrated increases in glass production rates and significant increases in sulfate incorporation and, therefore, waste loadings. This testing also demonstrated production rate increases and sulfur retention in the glass product at slightly higher than nominal glass processing temperatures. Subsequent tests demonstrated further enhancement of glass formulations for all of the LAW waste envelopes, increasing waste loading in the glass product and thereby reducing the amount of glass to be produced by the WTP for the same amount of waste processed [5, 6]. The main objective of the next phase of testing [7] was to determine the applicability of these improvements over the expected range of sodium and sulfur

concentrations for Hanford LAW. Five high waste loading glass formulations spanning the range of expected Na_2O and SO_3 concentrations in the Hanford LAW glasses were developed and subjected to melter testing. Glass formulation development and melter testing were designed such that the maximum achievable waste loadings could be determined.

For a large number of Hanford LAW streams, sulfur is the main component that limits waste loading in glass. However, for some LAW Envelope A streams with low sulfate contents, the alkali concentration becomes the waste loading limiting factor. In general, waste loading is limited by sulfur for wastes with a high sulfur-to-sodium ratio, while those with a low sulfur-to-sodium ratio are limited by sodium (or more specifically, total alkali (sodium plus potassium)). Minimizing overall glass volume across the entire LAW inventory, which is clearly of economic benefit, therefore, entails addressing both the sulfur limitation and the alkali limitation, depending on the waste type.

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 [8-11]. 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. The presence of the corrosive, low-melting, electrically conductive salt phase is undesirable from the perspectives of melter operation, melter lifetime, safety, and product quality. Accordingly, the WTP plans to control the composition of the LAW melter feed such that formation of a separate salt phase is avoided. Clearly, the control bounds that are imposed will determine the achievable waste loading limits and, therefore, will determine the waste processing rate for a given glass production rate (i.e., melter capacity).

For waste with low sulfur-to-sodium ratio, waste loading is instead limited by the total alkali content in the glass. At high alkali contents, glass leach resistance (PCT and VHT) decreases and the refractory corrosion rate in the glass melt increases. In addition, the melt viscosity may become too low and the electrical conductivity may become too high. Typically, however, the product leach resistance and the refractory corrosion properties are the first to be compromised as the alkali content in the glass is increased. Accordingly, the present work addresses LAW streams spanning a range of sulfur-to-sodium ratios with the objective of determining the maximum achievable waste loadings across this range, from sodium-limited to, sodium + potassium limited to, sulfur-limited formulations. As noted above, the broader intent is to develop a basis for estimation of the potential maximum waste loadings and corresponding glass volumes for the entire LAW inventory.

Under a separate contract to support the WTP Project, the VSL is developing and testing glass formulations for WTP to provide data to meet the WTP contract requirements and to support system design activities [12-17]. That work is based upon small-scale batch melts (“crucible melts”) using waste simulants. Selected formulations have also been tested in small-scale, continuously-fed, joule-heated melters (DM10 and DM100 systems) [10, 11, 18-27] and, ultimately, in the LAW Pilot Melter [28-39]. Such melter tests provide information on key process factors such as feed processing behavior, dynamic effects during processing, sulfate incorporation, processing rates, off-gas amounts and compositions, foaming control, etc., that cannot be reliably obtained from crucible melts. This sequential scale-up approach in the vitrification testing program ensures that maximum benefit is obtained from the more costly melter tests and that the most effective use is made of those resources.

Under the WTP support effort, VSL and EnergySolutions have developed and identified glass compositions for processing the Phase I LAW tank streams for the WTP. These compositions have been tested for processing and product quality requirements at various scales ranging from crucible melts of about 400 g up to the LAW Pilot Melter at processing rates in excess of 6600 kg/day (2000 kg/m²/day). The testing included the nominal feed compositions and those with $\pm 15\%$ variations in the waste simulants added to the melter feeds. The melter testing provided high confidence that the selected WTP compositions are unlikely to cause accumulation of a separate sulfate phase in the melter even at high feed processing rates. Feed processing characteristics and off-gas characteristics have been determined at various melter scales and data have been collected to support engineering and permitting requirements. Furthermore, statistically designed composition matrices were generated, and crucible melts of these glass compositions were prepared and characterized to qualify the glass composition region covering these LAW glass compositions selected for WTP waste processing [16, 17]. The selected WTP compositions have also been tested to ensure their compatibility with melter materials of construction. The glass formulation development and melter testing work for the selected WTP compositions have reached a level of maturity where the compositions can be used for waste processing at the WTP with relatively high confidence.

VSL/EnergySolutions have developed a LAW glass formulation correlation [40] that can be used to calculate glass compositions for waste processing, given the composition of an LAW stream. The correlation can be used to calculate compliant glass compositions for waste processing based on the ratios of sulfate to sodium (S/Na) and potassium to sodium (K/Na) in the LAW stream. The correlation uses a set of empirical relationships derived from the above array of test data to define waste loadings and the concentrations of glass former additives for a given LAW composition.

The glass formulation and melter testing work described in the Test Plan for this work [41] and presented in this Final Report expands this formulation approach to a wider range of LAW waste types, including those with high potassium concentration. Another objective is to assess the feasibility of formulating higher waste loading glasses without using Fe₂O₃ and TiO₂ as glass former additives. Based on the results of the previous studies, the effect of SnO₂ and V₂O₅ additions were further investigated to determine their utility in formulating higher waste loading LAW glasses. The results from these tests together with earlier work for ORP were

evaluated to recommend the work scope necessary to modify and update the current WTP LAW glass formulation correlation algorithm.

The glass formulation and melter testing presented in this Final Report is aimed at identifying glass compositions that have the potential to accommodate higher waste loadings than does the present WTP baseline, for LAW compositions specified by ORP [42]. A summary of the glass formulations previously developed for the four waste compositions is specified in Table 1.1. The four WTP LAW compositions used as part of the basis for the LAW correlation, LAWE3, LAWE4H, LAWE7H, and LAWE10H, were used as the starting points for development of the new formulations. These compositions are based on the compositions of LAW tanks AP-101, AN-105, AN-102, and AZ-102, thus covering the range of sulfate to sodium and potassium to sodium ratios expected in Hanford LAW. This information will provide ORP with a basis for evaluation of the likely potential for future enhancements of the WTP over and above the present well-developed baseline. In this regard, this work is complementary to, and necessarily of a more exploratory nature than the work in support of the current WTP baseline. It should be noted, therefore, that to the extent that the present effort was successful, considerable further work would be required to bring the level of confidence in the new glass compositions to a similar level of maturity to that of the current WTP baseline.

Based on the crucible formulation logic described below, DM10 tests were performed on each of the four selected formulations. The melter tests described in this report utilized waste simulants prepared and blended with glass formers at VSL to produce the melter feed. Sufficient feed was prepared to produce over half a metric ton of glass. Reductant in the form of sugar was added to the feed at a stoichiometric ratio of 0.5 (1 mole sucrose per 16 moles NO_x or 3 moles carbon per 4 moles NO_x). The waste simulant was prepared without sulfur and a corresponding portion of the sodium such that the sulfur content could be adjusted to desired concentrations by the addition of various combinations of NaOH and Na₂SO₄. These tests were performed at 1150°C and with a nominal target glass production rate of 2,250 – 2,500 kg/(m²·day). Each test segment was nominally 14 hours duration, which corresponds to three melter turnovers for the DM10 melter system that was employed. In each test sequence, composed of about 3 to 6 test segments, the sulfate content was progressively increased to the point at which a sulfate salt phase developed, indicating the limit of sulfate incorporation for that particular formulation. Quantitative measurements of glass production rates, melter operating conditions (temperatures, pressures, power, flows, etc.) and select gaseous emissions (NO_x, SO₂, CO, and acid gases) were made for each test. Glass samples taken from the glass pool and the air-lift discharged glass were inspected throughout testing to determine the limit of feed SO₃ concentration for operation of the melter without a separate sulfate phase.

The glass formulation development for this work followed a methodology developed by VSL/EnergySolutions during previous work. The methodology can be summarized as follows:

- Use existing glass formulation data and models to identify initial glass formulations for testing. The data used include ORP and WTP test data, data from other DOE programs, glass literature, geology, etc.

- Characterize the first set of glasses and use the information to refine the glass formulation for the next test set (active glass formulation design approach).
- Characterize glass samples for properties that are likely to be most challenging.
- For promising glasses, complete full characterization.
- Determine sulfur loading and processing characteristics through melter tests.

The glass formulation development work relied heavily on previous work performed for ORP [2, 5-7] and relevant WTP LAW glass formulation work [12-17]. Existing property-composition models were used to guide glass formulation development. However, since the existing models are not expected to be reliable in the new composition regions that were explored in this work, glass science knowledge and experience and information about the effect of various additives on glass structure and properties were used as additional tools to guide glass formulation development.

1.1 Test Objectives

The principal objective of the work described in this Final Report is to extend the glass formulation methodology developed in the earlier work [2, 5-7, 40] by development of acceptable glass compositions for four LAW compositions specified by ORP [42] that cover the range of sulfate to sodium and potassium to sodium ratios expected in Hanford LAW. Per the ORP scope of work [42], the glass formulations were designed to exclude titanium and iron as glass former additives, while tin and vanadium as glass former additives were evaluated for beneficial effects in increasing waste loading in the glasses. This was accomplished through a combination of crucible-scale tests and tests on the DM10 melter system. The DM10 was used for several previous tests on LAW compositions [2-7, 10, 11] to determine the maximum feed sulfur concentrations that can be processed without forming secondary sulfate phases on the surface of the melt pool. This melter is the most efficient melter platform for screening glass compositions over a wide range of sulfate concentrations and therefore was selected for the present tests. The current tests provide information on melter processing characteristics and off-gas data, including sulfur incorporation and partitioning. Other objectives of the work scope include study of the redox behavior of vanadium in LAW glasses, and measurement of the high temperature density, specific heat, and thermal conductivity of two LAW glasses, the results of which are reported separately.

The four waste types selected for testing, the starting glass compositions [43], and their respective target minimum waste loadings are given below:

- LAWE4H (based on LAW tank AN-105) with minimum waste loading of 27.18 wt%.
- LAWE3 (based on LAW tank AP-101) with minimum waste loading of 25.41 wt%.
- LAWE7H (based on LAW tank AN-102) with minimum waste loading of 16.22 wt%.
- LAWE10H (based on LAW tank AZ-102) with minimum waste loading of 6.20 wt%.

The objectives are:

- Develop glass formulations that are compliant with processing and product quality requirements for the above four waste streams, that exceed the minimum waste loadings, without using titanium and iron as glass former additives. Evaluate the use of tin and vanadium as glass former additives to increase waste loading.
- Determine the effect of redox state on the behavior of vanadium in the glass.
- Determine the maximum feed sulfur concentrations that can be processed on the DM10 melter without the formation of secondary sulfate phases for each of the four LAW glass formulations.
- Measure the high temperature specific heat, density, and thermal conductivity of two LAW glasses.
- Develop the work scope needed to update and modify the LAW correlation algorithm [40] using the new data on high waste loading LAW glasses developed for ORP.

The effect of redox state on the behavior of vanadium in the glass as well as the measurements of the high temperature specific heat, density, and thermal conductivity of two LAW glasses have been reported separately [44].

1.2 Quality Assurance

This work was conducted under a quality assurance program compliant with 10 CFR 830 Subpart A, NQA-1 (2000), and DOE Order 414.1C. This program was supplemented by a Quality Assurance Project Plan for ORP work [45] that is conducted at VSL. Test and procedure requirements by which the testing activities were planned and controlled are defined in the Test Plan [41]. The program is supported by VSL standard operating procedures that were used for this work [46]. The requirements of DOE/RW-0333P are not applicable to this work.

SECTION 2.0

WASTE SIMULANTS, GLASS FORMULATIONS AND FEED ANALYSIS

Glass formulation development and melter testing were conducted to identify compliant high waste loading glass formulations for Hanford LAW streams. The glass formulations covered a large portion of the expected range of Na₂O and SO₃ concentrations expected for LAW glasses. Based on the target Na₂O and SO₃ concentrations in the glasses, the glass formulation development was divided to focus on four LAW streams. The four waste types, their respective target sodium and sulfur loadings, and the starting glass compositions as given in the Test Plan [41], are:

- Region A: *starting from LAW correlation glass composition LAWE4H [43] (based on LAW tank AN-105) with a minimum waste loading of 27.18 wt%.*
- Region D: *starting from LAW correlation glass composition LAWE7H [43] (based on LAW tank AN-102) with minimum waste loading of 16.22 wt%.*
- Region F: *starting from LAW correlation glass composition LAWE10H [43] (based on LAW tank AZ-102) with minimum waste loading of 6.20 wt%.*
- Region G: *starting from LAW correlation glass composition LAWE3 [43] (based on LAW tank AP-101) with a minimum waste loading of 25.41 wt%.*

The waste simulant and glass formulations developed for each of the above composition regions are described in Sections 2.1 through 2.4. Other LAW composition regions with different sodium and sulfur concentrations have been studied previously [5-7].

The intent of the testing was, while targeting the above values, to determine the highest achievable Na₂O and SO₃ loadings for each of the waste streams. Thus, as the formulation work progressed and data from testing became available, the target Na₂O and SO₃ concentrations in the glass formulations were revised.

During the planning stages of this work, a total of 40 crucible melts were budgeted to develop glass formulations for all four regions. In order to satisfy budget constraints, more effort was focused on the measurement of glass properties that were judged to be most challenging for each set of glasses. Properties that were judged likely to be compliant with contract and processing requirements were either not measured, or measured only on select samples. The most economical and efficient way to make the best use of a limited number of crucible melts is to prepare and characterize them in very small sets using data from the previous sets to guide the design of the next set. In addition, it is most economical to limit initial characterization of the glasses to the properties that are likely to be the most challenging to meet; further

characterization need then be done only on those samples that pass the initial tests. However, since VHT was the most challenging criterion to meet and the VHT test duration is 24 days, time constraints did not always allow the above approach. In many cases, schedule constraints demanded that a larger number of crucible melts be made together and measurements of different glass properties be done in parallel in order to complete the work in the scheduled amount of time.

2.1 Region A (ORPLA) Waste Simulant and Glass Formulation

Glass formulation development and testing for Region A (ORPLA) were based on the composition of LAW material from Hanford tank AN-105. Details of the waste simulant and glass formulation development and testing are given below.

2.1.1 Region A (ORPLA) Waste Simulant for Tank AN-105

A LAW Envelope A waste simulant based on the composition data for tank AN-105, as given in a WTP Test Specification [47], was used as the basis for Region A glass formulations. The base waste composition incorporates TFCOUP [48] data, actual waste analysis data, and WTP flow sheet information. The sodium concentration in the simulant includes a 2.5 % increase to account for sodium additions in pretreatment [13, 49]. The nominal concentration, expressed in terms of the sodium molarity, was determined on the basis of melter feed rheology tests on similar formulations [50, 51]. The results of those tests led to the selection of 8.0 molar sodium as the nominal simulant concentration for the LAW AN-105 waste. This is the same concentration that was used in previous WTP melter tests for LAW AN-105 waste [18, 25, 52].

The nominal simulant formulation is given in Table 2.1. The LAW AN-105 simulant is a solution of predominantly sodium, aluminum, nitrate, nitrite and hydroxide. Since the simulant was similar to those tested previously at the VSL, it was not necessary to prepare and perform screening tests on new laboratory samples. A single simulant batch of about 32 gallons was prepared at VSL for the DM10 melter tests. Glass forming chemicals and sugar as a reductant were added directly to the 55-gallon drum, while the requisite combinations of sodium hydroxide and sodium sulfate were added to adjust the sodium and sulfur contents in smaller feed sub-batches for each test segment.

2.1.2 Region A (ORPLA) Glass Formulation

Glass formulation development for Region A (ORPLA) was based on the composition of the LAW AN-105 waste stream. The objective was to develop a glass formulation that can accommodate a minimum waste loading of 27.18 wt%. Since the Na₂O concentration in the waste is 77.25 wt% with 0.59 wt% SO₃, high sulfate loading in the glass was not a primary objective in glass formulation development for this region. To meet the minimum waste loading requirement, the target Na₂O and SO₃ loadings in the ORPLA glasses were 21 wt% and 0.16

wt%, respectively. Based on testing of a previous set of seventeen crucible melts with Na₂O concentrations in the range of 23.5 to 25 wt% [7], the minimum Na₂O concentration in the new formulations selected for testing was set at 24 wt%. Eight new crucible melts were prepared and characterized in an effort to identify a new glass formulation that meets all of the processing and product quality requirements [53, 54]. The target and analyzed compositions of the crucible melts are given in Table 2.2. The glass sodium content was initially set at a concentration of 24 wt% Na₂O, as was effectively tested before in glass ORPLA15 [7]. In contrast to ORPLA15, the new glass formulations did not have iron oxide as a glass former additive, which was compensated by small increases in the amounts of aluminum, boron, and zinc additives. Five of the eight new formulations were formulated with 24 wt% Na₂O, two with 25 wt% Na₂O, and one with 26 wt% Na₂O.

Tin was first considered as a potential glass former additive for Hanford LAW in work performed at VSL in 1999, while studying the effect of various group IV metals in the Periodic Table on LAW glasses [13]. Tin was observed to improve the LAW glass VHT performance but also to decrease sulfate solubility [55-57]. Since increasing sulfate solubility was the main focus of the glass development efforts at that time, less effort was directed at compositions containing tin. However, since recent projections show higher sodium additions in pretreatment at Hanford, there is increased interest in increasing sodium loadings in LAW glasses, which makes glass compositions with tin potentially more valuable. Titanium, zirconium, and tin have certain similarities in their electronic structure (d²s² for titanium and zirconium and d¹⁰s²p² for tin) which leads to some similarity in their properties. Zirconia is added primarily to improve the chemical durability of the glass, but it also tends to cause zircon crystallization if added in excess of about 5 wt%. Similarly, titanium is a known effective nucleating agent [58]. Substituting tin oxide for titania presents the advantage of potentially improving leach resistance without increasing the tendency for crystallization. In the new formulations, tin and zirconium oxide concentrations together were kept above 8.75 wt% to maintain leach resistance, but their molar ratios were varied from 1/3 : 2/3 (ORPLA18) to 1/2 : 1/2 (ORPLA19). A similar strategy was used to develop two more 24 wt%-Na₂O formulations, but without magnesium oxide addition (ORPLA22 and ORPLA23). Since the most common source of magnesium, olivine, brings about 8 wt% iron oxide as fayalite (Fe₂SiO₄) mixed with forsterite (Mg₂SiO₄), iron oxide is present in glass formulations containing magnesium, even though iron oxide is not specifically added as a glass former. The removal of magnesium allows testing of glass compositions containing no iron oxide. In one of the 24 wt% Na₂O formulations (ORPLA20), the alumina content was decreased by 3 wt% with a corresponding increase in the silica content, which is predicted to decrease Vapor Hydration Test (VHT) alteration rate and increase sulfate solubility. This glass did have the highest sulfate solubility for Region A glasses and also showed acceptable performance on VHT.

The successful strategy with lower alumina in ORPLA20 was further tested at 25 wt% Na₂O in ORPLA21. Glasses devoid of magnesium and iron were also tested at 25 and 26 wt% Na₂O. For these very high Na₂O glasses, the properties of most concern are VHT alteration rate and K-3 refractory corrosion. In order to reduce K-3 refractory corrosion, Cr₂O₃ was added at a concentration of about 0.5 wt% in addition to maintaining Al₂O₃, SiO₂, SnO₂, and ZrO₂ concentrations at high levels [7]. VHT alteration rates of these glasses were high, but remained

within the contractual limit. The four glasses with the highest sulfate solubilities were tested for their K-3 corrosion characteristics, and only ORPLA20 showed acceptable behavior.

Target and analyzed compositions of the ORPLA glasses are given in Table 2.2. Glass compositions were determined by X-ray Fluorescence Spectroscopy (XRF) on powdered glass samples, except for B_2O_3 , which was measured by Direct Current Plasma – Atomic Emission Spectroscopy (DCP-AES) after acid dissolution. As is evident from the table, the target and analyzed compositions show good agreement. Testing of all formulations started with glass preparation and optical microscopic evaluation of the as-melted sample. Glass samples were heat treated for 20 hours at $950^\circ C$ and then evaluated for secondary phases. Observations of the as-melted and heat treated glasses are given in Table 2.3. All of the as-melted glasses appeared clear with some containing small amounts (< 0.1 vol%) of chromium oxide crystals. Since these crystals are not detected after heat treatment, they can be attributed to incomplete dissolution of the chromium oxide additive. Some of the heat treated glasses showed spinel crystals. Since the glasses have high ZrO_2 contents, Na-Zr-silicate crystals were present in most of them except for ORPLA20 with a high ZrO_2 content of 6.0 wt% and ORPLA19 with the lowest ZrO_2 content of 3.93 wt%. Sn-containing crystals also were detected in these glasses, with the exception of ORPLA20, with a comparatively lower SnO_2 concentration, combined with lower Al_2O_3 and higher SiO_2 concentrations.

The sulfate solubilities of the ORPLA glass compositions were assessed by batch saturation tests. This is a crucible-scale screening test that is used to obtain an indication of the extent of sulfur incorporation that will be obtained under actual melter operating conditions, which is, of course, the measure that is of practical importance. The results of these screening tests are then used to guide the range of sulfur concentrations over which the melter tests are performed. The batch saturation tests were performed by remelting finely ground samples of the glasses with an excess of sulfate amounting to 4 wt% SO_3 if all of it were retained in the glass. The remelted glass samples are identified with an S4 at the end of the sample name. Results of sulfate batch saturation tests are given in Table 2.4 and Figure 2.1. The results identified as “after acid wash” are analyses of glass samples remelted with 4 wt% SO_3 after grinding and washing to remove any interstitial sulfate phases, to ensure that only the SO_3 that is dissolved in the glass is measured. The sulfate retentions in the glasses (“after acid wash”) varied from about 0.30 wt% SO_3 for ORPLA18 to 0.41 wt% SO_3 for ORPLA25.

VHT and PCT results are summarized in Table 2.5 and illustrated in Figures 2.2 and 2.3. The results show that although none of the new formulation exceeded the VHT alteration rate requirement of $50\text{ g/m}^2/\text{day}$, three of these ORPLA glasses showed high alteration depths. This was not unexpected because the VHT requirement becomes more challenging as the alkali content of the glasses is increased, which is why all of the glasses were formulated with high concentrations of SnO_2 and ZrO_2 in order to counteract the effects of high alkali. As expected, VHT alteration rates increase with increases in Na_2O content. Comparison of the VHT results of ORPLA20 and ORPLA18 shows that increases in SiO_2 concentration with a corresponding decrease in the Al_2O_3 concentration, leads to a decrease in the VHT alteration rate. Removal of MgO and Fe_2O_3 from the glass composition combined with higher SnO_2 concentration also seems to improve the VHT performance of these high alkali glasses. PCT releases for the glasses

given in Table 2.5 and Figure 2.3 show that all of the glasses met the ILAW product quality requirement of normalized mass loss of less than 2 g/m² for B, Na, and Si. For the eight ORPLA glasses that were studied, the PCT releases do not show any clearly discernable effect of glass composition.

The viscosities and electrical conductivities of three of the glasses at select temperatures are given in Table 2.6. Viscosities and electrical conductivities of the remaining glasses were not measured because they failed the K-3 corrosion criterion. All of the measured viscosities and electrical conductivity values are in the acceptable range for melt processing [53] at WTP. Note that the glasses were designed to have viscosities towards the high limit for acceptability in order to reduce refractory corrosion.

K-3 refractory corrosion is a significant concern, due to the high alkali content of the ORPLA glass formulations. The four glasses with the highest alkali contents and sulfate solubilities were tested for their K-3 corrosion characteristics. K-3 refractory corrosion test results for these glasses are given in Table 2.7 and Figure 2.4, where they are compared to the results for some of the previously tested ORP LAW glasses [7]. All but one of the glasses, ORPLA20, had unacceptable K-3 corrosion characteristics, which could impact melter life. Acceptability of the corrosion characteristics of a glass composition is somewhat subjective because a glass composition that shows slightly higher K-3 corrosion, but allows higher waste loading, may be a more economic choice than one with lower K-3 corrosion and lower waste loading. However, for WTP LAW glass formulation development, a neck corrosion of 0.035 inches on the 6-day K-3 coupon corrosion test at 1208°C has been used as an acceptance limit. For the current LAW glass formulation development work for ORP, since higher waste loading compositions are being explored, a slightly higher neck corrosion value of 0.040 inches has been used as a guide for acceptable corrosion characteristics.

With the exception of K-3 corrosion, all eight of the new ORPLA glass formulations met the processing and product quality requirements for melt processing at WTP. However, only one of the glasses, ORPLA20, met the K-3 corrosion criterion and was, therefore, selected for DM10 melter tests. The measured properties of the glass ORPLA20 are compared to the ILAW performance requirements [53, 54] in Table 2.8. Density and glass transition temperature (T_g) measurements and canister centerline cooling (CCC) heat treatments were not conducted on ORPLA20 samples because the glass is expected to be acceptable with respect to these properties. The only requirement for T_g is that it be measured and reported. Even though density was not measured for the ORPLA20 crucible glass, the density was measured for a glass sample from the DM10 melter test and the value is within the acceptable limit. In addition, none of the measured densities of LAW glasses prepared for WTP or ORP exceeded or even approached the limit of 3.7 g/cc. Since the sample heat treated at 950°C for 20 hours showed only 0.3 vol% of crystals, CCC treatment is not expected to cause extensive crystallization. Although cooling of the glass discharged from the DM10 melter occurs faster than in a WTP LAW canister, examination of cooled ORPLA20 glass samples from the DM10 melter corroborated this expectation in that very few crystals were present in the discharge glass samples.

The composition of the ORPLA20 glass used in melter tests is given in Table 2.9 along with the oxide contributions from the LAW AN-105 waste simulant and from the glass former additives. The simulant was prepared with no SO_3 and the sulfur concentration was increased in steps during the melter tests by adding the appropriate amounts of Na_2SO_4 and NaOH to the feed. The melter feed was prepared at a Na_2O concentration of 23.25 wt% (for zero sulfate) in order to accommodate Na_2SO_4 and NaOH additions, without increasing the Na_2O concentration above 24.0 wt% while accommodating up to 0.96 wt% SO_3 . The types and amounts of glass former additives used to prepare the melter feed along with the target feed properties are given in Table 2.10a. The glass former additives are the same as those planned for use at the WTP, with the exception of chromium and tin, which would be new additives. The amounts of Na_2SO_4 and NaOH added to the feed to obtain 24 wt% Na_2O and 0.20 to 0.90 wt% SO_3 are given in Table 2.10b.

2.2 Region D (ORPLD) Waste Simulant and Glass Formulation

Glass formulation development and testing for Region D (ORPLD) were based on the composition of LAW material from Hanford tank AN-102. Details of the waste simulant and glass formulation development and testing are given below.

2.2.1 Region D (ORPLD) Waste Simulant for Tank AN-102

A LAW Envelope C waste simulant based on the composition data for tank AN-102, as given in a WTP Test Specification [47], was used as the basis for ORPLD glass formulations. The base waste composition incorporates TFCOUP [48] data, actual waste analysis data, and WTP flow sheet information. The sodium concentration in the simulant includes a 17.65 % increase to account for sodium additions in pretreatment [13, 49]. The nominal concentration, expressed in terms of the sodium molarity, was estimated on the basis of melter feed rheology tests on similar formulations [50, 51]. The concentration of the simulant used in melter tests was 8.0 molar sodium. This is higher than that used in previous WTP LAW melter tests [24, 27] because of the higher waste loading in the ORPLD glasses, but similar to previous ORP melter tests [7]. It is considered that any further increase in waste loading would still not justify increasing the simulant concentration beyond 8 Molar Na due to concerns related to sodium nitrate crystallization [51].

The nominal simulant formulation is given in Table 2.11. The LAW AN-102 simulant is a solution of predominantly sodium, nitrate, nitrite, and sulfate. Preparation of the waste simulant and melter feed were done in a manner similar to that for ORPLA simulant, which is described in Section 2.1.1.

2.2.2 Region D (ORPLD) Glass Formulation

Glass formulation development for Region D (ORPLD) was based on the composition of the LAW AN-102 waste stream. The objective was to develop a glass formulation that can accommodate a minimum waste loading of 16.22 wt%, as achieved in the LAW correlation glass LAWE7H [52]. Earlier studies with this waste composition for ORP resulted in the development of a high waste loading glass (24.7 wt%) with a target SO_3 loading of about 0.6 wt%. Building on the previous results, six new crucible melts were prepared in an effort to identify a glass formulation that meets all processing and product quality requirements, but with higher waste loading. This is a challenging region for glass formulation because the alkali content is still relatively high, but the target SO_3 loading is higher in Region D glasses than for Region A, Region B, and Region C glasses [7]. The target and analyzed compositions of the new glasses are given in Table 2.12. To increase sulfate solubility, 1 to 3 wt% of V_2O_5 was added to all six of the new ORPLD glass formulations, and iron was removed as a glass former additive. Note, however, that about 0.3 wt% of Fe_2O_3 is still present in the final glass compositions because of contribution from olivine used as a magnesium source. The waste loading was increased in steps, from 25 wt%, to 26 and 27 wt%, leading to glasses containing 21, 22 and 23 wt% Na_2O , respectively. The zirconia concentration was increased from 3 wt% in ORPLD4 to 4 wt% in the other five glasses, and tin oxide was added to ORPLD7, ORPLD8 and ORPLD9 to improve the performance on PCT, VHT, and K-3 refractory corrosion tests. In order to reduce K-3 refractory corrosion, Cr_2O_3 was added at a concentration of about 0.5 wt% to all of the glasses.

Target and analyzed compositions of the ORPLD glasses are given in Table 2.12. Testing and analysis of the glasses followed the same methods used for ORPLA glasses, which are described in Section 2.1.2. As is evident from the table, the target and analyzed compositions show good agreement. Glass samples were heat treated for 20 hours at 950°C and evaluated for secondary phases. Observations of the as-melted, and heat treated glasses are given in Table 2.13. All of the as-melted glasses appeared clear with small amounts (0.1 vol% or less) of crystals. The heat treated glasses also showed little crystallization (0.3 vol% or less on average).

The sulfate solubilities of the ORPLD glass compositions were assessed by batch saturation tests. The batch saturation tests are described in Section 2.1.2 and the results of the tests are given in Figure 2.1 and Table 2.14. The sulfate solubilities of the ORPLD glasses varied little in the series, from 0.86 to 0.95 wt% by batch saturation tests. VHT and PCT results are summarized in Table 2.15 and illustrated in Figures 2.2 and 2.3. All six of the glasses met the PCT release and VHT alteration rate limits. ORPLD9 with the highest Na_2O content of 23 wt% and V_2O_5 content of ~3 wt% showed the highest VHT alteration rate of 42 g/m²/day which is close to the limit of 50 g/m²/day. The viscosities and electrical conductivities of the six glasses at select temperatures are given in Table 2.16. The measured values are all within the acceptable processing ranges, but the viscosities are towards the lower end of the range which is a concern with respect to K-3 refractory corrosion. K-3 refractory corrosion test results for the four glasses with the highest waste loadings are given in Table 2.17 and Figure 2.4. Only ORPLD6 met the limit of ≤ 0.040 inches of neck loss in the K-3 corrosion test.

Of the six ORPLD glass formulations tested, only one, ORPLD6, met all processing and product quality requirements and was, therefore, selected for melter testing. Note that similar to Region A glasses, K-3 refractory corrosion was the most constraining glass property. The measured properties of the glass ORPLD6 are compared to the ILAW performance requirements [53, 54] in Table 2.18. Density and glass transition temperature measurements, and canister centerline cooling (CCC) heat treatments were not conducted on ORPLD6 crucible glass, but density was measured on the glass produced in the DM10 melter. Examination of cooled ORPLD6 glass samples from the melter showed little crystallization, indicating that the glass is unlikely to show substantial crystallization on CCC heat treatment.

The composition of the ORPLD6 glass used in melter tests is given in Table 2.19 along with the oxide contributions from the LAW AN-102 waste simulant and from the glass former additives. The simulant was procured with no SO_3 and the sulfur concentration was increased in steps during the melter tests by adding the appropriate amounts of Na_2SO_4 and NaOH to the feed. The melter feed was procured at a Na_2O concentration of 20.44 wt% in order to accommodate Na_2SO_4 (for SO_3 up to 2 wt%) and NaOH additions, without increasing the Na_2O concentration above 22.0 wt%. The types and amounts of glass former additives used to prepare the melter feed along with the target feed properties are given in Table 2.20a. The glass former additives are the same as those planned for use at the WTP, with the exception of chromium and vanadium, which would be new additives. The amounts of Na_2SO_4 and NaOH added to the feed to obtain 22.0 wt% Na_2O and 0.0 to 1.3 wt% SO_3 are given in Table 2.20b.

2.3 Region F (ORPLF) Waste Simulant and Glass Formulation

Glass formulation development and testing for Region F (ORPLF) were based on the composition of LAW material from Hanford tank AZ-102. Details of the waste simulant and glass formulation development and testing are given below.

2.3.1 Region F (ORPLF) Waste Simulant for Tank AZ-102

A LAW Envelope B waste simulant based on the composition data for tank AZ-102, as given in a WTP Test Specification [47], was used as the basis for Region F glass formulations. The base waste composition incorporates TFCOUP [48] data, actual waste analysis data, and WTP flow sheet information. The sodium concentration in the simulant includes a 5.33% increase to account for sodium additions in pretreatment [13, 49]. The nominal concentration, expressed in terms of the sodium molarity, was estimated on the basis of melter feed rheology tests on similar formulations [50, 51]. The concentration of the simulant used in melter tests was 5.5 Molar sodium. This is higher than that used in previous melter tests [22, 37] because of the higher waste loading in the ORPLF glasses. Laboratory testing for this feed simulant was performed at 5 Molar Na, based on extrapolation of data from previously measured feed rheologies [7, 51]. Results from the feed rheology tests given in Figure 2.5, indicated that a slight increase in the concentration of the feed can be accommodated. Accordingly, the feed for the DM10 melter test was prepared at a concentration of 5.5 Molar Na.

The nominal simulant formulation is given in Table 2.21. The LAW AZ-102 simulant is a solution of predominantly sodium, nitrate, and sulfate. Preparation of the waste simulant and melter feed were done in a manner similar to that for ORPLA simulant, which is described in Section 2.1.1.

2.3.2 Region F (ORPLF) Glass Formulation

Glass formulation development for Region F (ORPLF) was based on the composition of the LAW AZ-102 waste stream. Fourteen crucible melts were prepared in an effort to identify a glass formulation that meets all processing and product quality requirements. The target and analyzed compositions of the glasses are given in Table 2.22. Unlike ORPLA and ORPLD glasses, ORPLF glasses were designed at lower sodium concentrations since sulfate content is the highest for this waste. Addition of lithium and higher amounts of calcium were also used to increase sulfate solubility. Since these glass compositions contained fairly large concentrations of both Na_2O (10 – 13 wt%) and Li_2O (3.45 – 5 wt%) to increase waste loading, K-3 refractory corrosion was a concern. Accordingly, in order to reduce K-3 refractory corrosion, Al_2O_3 , SiO_2 , and ZrO_2 concentrations were maintained at high levels in all the glasses, and Cr_2O_3 was added at a concentration of about 0.5 wt% to all of the glasses. To improve VHT performance, ZrO_2 was maintained at high concentrations (> 3.8 wt%) and SnO_2 was also tested in six of the glasses [55-57]. Since the target SO_3 loadings were higher in ORPLF glasses as compared to the ORPLA and ORPLD glasses, V_2O_5 was also added to all of the ORPLF glass formulations.

The first series of ORPLRF glasses were prepared with waste loadings in the range of 12 to 16 wt%. The corresponding Na_2O concentrations varied from 10 to 13 wt% with Na_2O at 10 wt% in ORPLF1, 11wt% in ORPLF2, 12 wt% in ORPLF3 and ORPLF4, and 13 wt% in ORPLF5 and ORPLF6. Note that with this increasing waste loading, target sulfate concentrations also increased from 1.6 to 2.1 wt% SO_3 . In this series, the effect of increasing V_2O_5 concentration by about 1.25 wt% and decreasing the Al_2O_3 concentration by the same amount on sulfate solubility was also tested in two sets of glasses (ORPLF3 and ORPLF4, and ORPLF5 and ORPLF6). Results from the first series of ORPLF glasses showed that VHT alteration rate requirement can be met fairly easily, thus reducing the need for SnO_2 addition, while Li_2O and V_2O_5 concentrations needed to be increased to improve sulfate solubility.

In the following series of ORPLF melts, Li_2O concentration was increased to 4.35 wt% in ORPLF7 and 5 wt% in ORPLF8, but maintained at 3.5 wt% in ORPLF9 to ORPLF13. Higher Li_2O concentrations clearly increased the sulfate loading, although this also increased the corrosion of K-3 refractory by the glass melt. V_2O_5 concentrations were tested at 2.5 wt% or 2.75 wt%. To completely eliminate iron from the glass composition, magnesium was also removed in ORPLF13 and ORPLF4 and the CaO concentration was increased. Phosphorous was also considered as a new additive for improved sulfate loading in ORPLF9, where 2 wt% P_2O_5 was added with decreases in Al_2O_3 (less 1 wt%), B_2O_3 (less 0.65 wt%), and SiO_2 (less 0.32 wt%).

Target and analyzed compositions of the ORPLF glasses are given in Table 2.22. Testing and analysis of the glasses followed the same methods used for ORPLA glasses, which are described in Section 2.1.2. As is evident from the table, the target and analyzed compositions show good agreement. Glass samples were heat treated for 20 hours at 950°C and then evaluated for secondary phases. Observations of the as-melted and heat treated glasses are given in Table 2.23. All of the as-melted glasses appeared clear with very small amounts (< 0.2 vol%) of crystals. The heat treated glasses also showed little crystallization (≤ 0.3 vol%).

The sulfate solubilities of the ORPLF glass compositions were assessed by batch saturation tests as described in Section 2.1.2. The results of the tests are given in Figure 2.1 and Table 2.24. The measured sulfate concentrations in the ORPLF glasses varied from 1.19 to 1.45 wt% after acid washing of the saturated glass and 1.39 to 1.86 wt% before the acid wash, with the highest sulfate concentrations in ORPLF7 (4.35 wt% Li_2O) and ORPLF8 (5 wt% Li_2O).

VHT and PCT results are summarized in Table 2.25 and illustrated in Figures 2.2 and 2.3. All of the glasses met the PCT release and VHT alteration rate limits. VHT alteration rate for glass ORPLF9 with 2 wt% P_2O_5 addition was the highest among all fourteen glasses. The viscosities and electrical conductivities of eleven of the ORPLF glasses at select temperatures are given in Table 2.26. All of the viscosity and electrical conductivity values are in the acceptable range for processing, but, because of the Li_2O addition, the viscosity values are towards the lower part of the acceptable range. Seven of the ORPLF glasses with some of the highest sulfate solubilities were tested for their K-3 corrosion characteristics. K-3 refractory corrosion test results for the glasses are given in Table 2.27 and Figure 2.4. The concern in this case is no longer the corrosion of the K-3 material at the neck (melt-air interface) and, in fact, all of the glasses passed the requirement of less than 0.04 inches neck loss. However, the presence of lithium in the glass melt combined with low viscosity leads to infiltration of the K-3 material at the grain boundaries [59] with fairly large penetration depth and formation of wide cracks within the test coupon. Large cracks were observed in K-3 coupons exposed to glass ORPLF8 and, to a much lesser extent, in K-3 coupons exposed to ORPLF4, ORPLF7, and ORPLF10. Two of these glasses, ORPLF7 and ORPLF10, were tested twice to confirm their K-3 corrosion characteristics before selection of a glass composition for DM10 melter tests. In one of the tests, the low viscosity led to molten glass splashing on the alumina refractory cover that holds the coupon and serves as the lid of the platinum crucible in which the test is conducted (with bubbling), which contaminated the melt with alumina and compromised the test.

Among the fourteen ORPLF glass formulations tested, the two highest sulfate solubilities were observed for glasses ORPLF7 and ORPLF8. However, these glasses also showed some cracking of the K-3 refractory coupons. After duplicate K-3 corrosion tests, ORPLF7 was selected for DM10 melter tests because it met all processing and product quality requirements and showed the highest sulfate solubility. The measured properties of glass ORPLF7 are compared to the ILAW performance requirements [53, 54] in Table 2.28. Density and glass transition temperature measurements and canister centerline cooling (CCC) heat treatments were not conducted on ORPLF7 crucible glass but the density was measured on a glass sample from DM10 melter testing. Examination of cooled ORPLF7 glass samples from the melter tests

showed little crystallization, indicating that the glass is unlikely to show substantial crystallization on CCC heat treatment.

The composition of the ORPLF7 glass used in melter tests is given in Table 2.29 along with the oxide contributions from the LAW AZ-102 waste simulant and from the glass former additives. The simulant was procured with no SO_3 and the sulfur concentration was increased in steps during the melter tests by adding the appropriate amounts of Na_2SO_4 and NaOH to the feed. The melter feed was prepared at a Na_2O concentration of 10.45 wt% in order to accommodate Na_2SO_4 and NaOH additions without increasing the Na_2O concentration above 12.00 wt%. The types and amounts of glass former additives used to prepare the melter feed along with the target feed properties are given in Table 2.30a. The glass former additives are the same as those planned for use at the WTP, with the exception of chromium, and vanadium, which would be new additives. The amounts of Na_2SO_4 and NaOH added to the feed to obtain 12.00 wt% Na_2O and 0.0 to 1.7 wt% SO_3 are given in Table 2.30b.

2.4 Region G (ORPLG) Waste Simulant and Glass Formulation

Glass formulation development and testing for Region G (ORPLG) were based on the composition of LAW material from Hanford tank AP-101. Details of the waste simulant and glass formulation development and testing are given below.

2.4.1 Region G (ORPLG) Waste Simulant for Tank AP-101

A LAW Envelope A waste simulant based on the composition data for tank AP-101, as given in a WTP Test Specification [47], was used as the basis for ORPLG glass formulations. The base waste composition incorporates TFCOUP [48] data, actual waste analysis data, and WTP flow sheet information. The sodium concentration in the simulant includes a 2.5 % increase to account for sodium additions in pretreatment [13, 49]. The nominal concentration, expressed in terms of the sodium molarity, was estimated on the basis of melter feed rheology tests on similar formulations [50, 51]. The concentration of the simulant used in DM10 melter tests was 8.45 Molar sodium.

The nominal simulant formulation is given in Table 2.31. The LAW AP-101 simulant is a solution of predominantly aluminum, sodium, potassium, nitrate, nitrite, carbonate, and sulfate. Preparation of the waste simulant and melter feed were done in a manner similar to that for ORPLA simulant, which is described in Section 2.1.1.

2.4.2 Region G (ORPLG) Glass Formulation

Glass formulation development for Region G (ORPLG) was based on the composition of the LAW AP-101 waste stream. The objective was to develop a glass formulation that can accommodate a minimum waste loading of 25.41 wt%. The waste components that are important

in formulating glasses for this waste are Na₂O (71.67 wt%), K₂O (19.61 wt%), and SO₃ (1.39 wt%). The high alkali content of the waste from a combination of Na₂O and K₂O is the primary challenge in glass formulation. While sulfate loading in the glass is not very high, the effect of high alkali content from a combination of Na₂O and K₂O on sulfate solubility is not well understood. Target and analyzed compositions of the ORPLG glasses are given in Table 2.32. ORPLG glasses were initially formulated with progressively higher waste loadings. The waste loading increases were designed such that Na₂O loadings in the glasses increased from 18.5 wt% to 21.5 wt% in steps of 0.5 wt% at lower Na₂O concentrations and in steps of 0.25 wt% at the higher Na₂O concentrations. All of the waste components increased with waste loading, with K₂O increasing from 5.06 wt% to 5.88 wt% as the Na₂O concentration increased from 18.5 wt% to 21.5 wt%. The additive blend was kept similar to those selected for ORPLA20, keeping ZrO₂ + SnO₂ between 8.5 and 9 wt% for all but one of the glasses, and silica above 40.5 wt%. CaO and Al₂O₃ concentrations were decreased in an attempt to improve the performance on VHT, especially in the presence of high K₂O concentrations [60]. Since VHT was a property of prime concern, it was measured for all samples before the selection of samples for K-3 corrosion tests. In order to reduce K-3 refractory corrosion, Cr₂O₃ was kept at a concentration of ~0.6 wt% in all of the glasses. The sulfate solubilities were generally higher in the glasses with higher waste loading but VHT alteration rates rose sharply as the Na₂O concentration exceeded 20.5 wt%. At the 20.5 wt% Na₂O concentration, the glass also contains 5.61 wt% K₂O. Fe₂O₃ was not used as a glass former additive in any of the glasses. In two of the glasses (ORPLG5 and ORPLG11) MgO also was removed as an additive so that Fe₂O₃ from the MgO source, olivine, could be avoided. In glass ORPLG12, 2 wt% P₂O₅ was added with a corresponding decrease in the ZrO₂ concentration, which led to much increased VHT alteration rate.

Target and analyzed compositions of the ORPLG glasses are given in Table 2.32. Testing and analysis of the glasses followed the same methods used for ORPLA glasses, which are described in Section 2.1.2. As is evident from the table, the target and analyzed compositions show good agreement. Glass samples were heat treated for 20 hours at 950°C and evaluated for secondary phases. Observations of the as-melted, and heat treated glasses are given in Table 2.33. All of the as-melted glasses appeared clear with small amounts (0.2 vol% or less) of crystals. The heat treated glasses also showed little crystallization (0.3 vol% or less).

The sulfate solubilities of the ORPLG glass compositions were assessed by batch saturation tests. The batch saturation tests are described in Section 2.1.2 and the results of the tests are given in Figure 2.1 and Table 2.34. The sulfate solubilities of the ORPLG glasses varied from 0.36 to 0.49 wt% by batch saturation tests and generally increased with increased waste loading. In addition to batch saturation tests, the sulfate solubility of the ORPLG9 glass composition was determined by gas bubbling. Two samples of ORPLG9, one with 0.59 wt% Cr₂O₃ and another with 1.0 wt% Cr₂O₃, were used in the measurements. Results of these tests are given Figure 2.6 along with the results from some earlier tests on similar glasses developed for ORP. The sample with 0.59 wt% Cr₂O₃ showed a sulfate solubility of 0.65 wt% and the sample with 1.0 wt% Cr₂O₃ showed sulfate solubility of 0.55 wt%. More interesting is the observation that the onset of a secondary sulfate layer occurred at an SO₃ concentration of about 0.3 wt% in the sample with 0.59 wt% Cr₂O₃, whereas it occurred at an SO₃ concentration of less than

0.2 wt% in the sample with 1.0 wt% Cr₂O₃. The implications of this observation are discussed later in Section 5.0.

VHT and PCT results are summarized in Table 2.35 and illustrated in Figures 2.2 and 2.3. All twelve glasses met the PCT release limit, but the VHT alteration rate limit was reached in ORPLG9 (21 wt% Na₂O + 5.75 wt% K₂O) and exceeded in ORPLG10 (highest waste loading) and ORPLG12 (with added P₂O₅). The viscosities and electrical conductivities of eleven of the ORPLG glasses at select temperatures are given in Table 2.36. All of the viscosities and electrical conductivity values are in the acceptable range for processing. Similar to ORPLA glasses, the ORPLG glasses were designed to have viscosities towards the higher end of the acceptable range in order to reduce refractory corrosion. Eight ORPLG glasses with the higher waste loadings (> 27.2 wt%) were tested for their K-3 corrosion characteristics. K-3 refractory corrosion test results for these glasses are given in Table 2.37 and Figure 2.4. Only one of the glasses, ORPLG11 (highest waste loading) had clearly unacceptable K-3 corrosion characteristics with a neck loss of 0.06 inches. The depth of the reaction zone into the K-3 coupon is fairly high in these samples, especially ORPLG9. This has been observed before with low viscosity glasses and glasses containing Li₂O, but not in the ORPLG-type of glasses. It is likely that this could impact melter life but further detailed K-3 corrosion studies will be needed to determine the effect of very high alkali content from a combination of Na₂O and K₂O on K-3 corrosion.

Of the twelve ORPLG glass formulations tested, ORPLG7 and ORPLG8 are formulations with high waste loading that also met all processing and product quality requirements. Those were, therefore, recommended by VSL/EnergySolutions for DM10 melter tests. However, ORP selected ORPLG9 for the melter tests in order to determine the processing characteristics of a glass formulation that is at the limit of the acceptable range for one or more properties. The selected glass, ORPLG9, has a VHT alteration rate of 41-50 g/m²/day as compared to the limit of 50 g/m²/day and showed a K-3 neck corrosion of 0.038 inches versus the limit of 0.040 inches. The measured properties of the glass ORPLG9 are compared to the ILAW performance requirements [53, 54] in Table 2.38. Density and glass transition temperature measurements and canister centerline cooling (CCC) heat treatments were not conducted on ORPLG9 crucible glass, but the density was measured on the melter glass and was found to be well below the limit of 3.7 g/cc. Examination of cooled ORPLG9 glass samples from the melter showed little crystallization, indicating that the glass is unlikely to show substantial crystallization on CCC heat treatment.

The composition of the ORPLG9 glass used in melter tests is given in Table 2.39 along with the oxide contributions from the LAW AP-101 waste simulant and from the glass former additives. The simulant was prepared with no SO₃ and the sulfur concentration was increased in steps during the melter tests by adding the appropriate amounts of Na₂SO₄ and NaOH to the feed. The melter feed was prepared at a Na₂O concentration of 20.21 wt% in order to accommodate Na₂SO₄ and NaOH additions, without increasing the Na₂O concentration above 21.0 wt%. The types and amounts of glass former additives used to prepare the melter feed along with the target feed properties are given in Table 2.40a. The glass former additives are the same as those planned for use at the WTP, with the exception of chromium and tin, which would be

new additives. The amounts of Na₂SO₄ and NaOH added to the feed to obtain 21.0 wt% Na₂O and 0.0 to 0.3 wt% SO₃ are given in Table 2.40b.

2.5 Sugar Additions

With high nitrate feeds, the addition of reductants is necessary in order to control melt foaming. Sugar, which was used for this purpose at West Valley, has also been selected as the baseline reductant for the WTP. The amount of sugar required increases with the amount of nitrates present in the feed and decreases with the amount of waste organics present in the feed, which themselves act as reductants. Excessive additions of reductants can be deleterious, leading to over-reduction of the melt and formation of sulfides and molten metals. Consequently, the oxidants and reductants in the feed must be suitably balanced. The basis for achieving this balance was developed by VSL and EnergySolutions for the vitrification of high-sodium-nitrate feeds at Savannah River's M-Area and has been successfully applied to the processing of a wide variety of simulated WTP feeds over the past six years. In developing this approach, we elected to conservatively adopt the most reducing potential reaction as the basis for the *definition* of a "sugar" or stoichiometric ratio of 1.0 as a result of concerns for over-reducing the melt. Such a reaction, using sodium salts as an example, is:

Fundamentally, the basis that is selected is simply a convention, since the precise stoichiometry of the reactions involved is neither known nor constant under the conditions prevailing in the melter. However, with this convention, a sugar ratio of 1.0 corresponds to one mole of sucrose per eight moles of nitrate or, more generally, 1.5 moles of organic carbon per mole of nitrate. It is then expected that significantly less sugar than this will be required in practice. The empirically determined amount required to successfully control melt foaming without significantly reducing the glass melt was found to correspond to a ratio of 0.5 when any nitrites present were counted as nitrates (i.e., 0.75 moles of organic carbon per mole of nitrate + nitrite). This approach has been employed for all WTP melter testing. It is, however, expected that slight variations around the nominal value of 0.5 may be necessary to account for differences in the reducing power of waste organics in comparison to sugar, particularly for LAW streams that are high in organics.

As an example, the calculation of the amount of sugar needed for the present LAW AN-105 (Envelope A) feed to achieve a sugar ratio of 0.5 proceeds as follows:

- One liter of 8 Molar sodium simulant contains 1.857 moles of nitrite and 2.048 moles of nitrate, giving a total of 3.905 moles of NO_x (see Table 2.1)
- The required total amount of organic carbon for a sugar ratio of 0.5 is $3.905 \times 0.75 = 2.929$ moles
- One liter of simulant contains 0.174 moles of organic carbon (see Table 2.1)
- Therefore, $2.929 - 0.174 = 2.755$ moles of organic carbon must be added.

Since the molecular weight of sucrose is 342 g, $2.755 \times 342/12 = 78.5$ g sugar must be added per liter of simulant, as shown in Table 2.10.a.

2.6 Analysis of Melter Feed Samples

2.6.1 General Properties

Feed samples from melter tests were analyzed to confirm physical properties and chemical composition. Samples were taken from residual composite melter feed, from individual test segments, and feed prior to adjusting the sulfur content. Sample names, sampling dates, measured properties and comparisons with feed analysis for similar waste streams [2, 3, 6, 22, 24, 26, 61-63] are provided in Table 2.41. The average measured glass yield for the melter samples was less than 6% below the target values (on a mass per unit mass basis) validating the use of the target value for calculating glass production rates. This small low bias for glass yield and density is observed in most LAW feeds due perhaps to high estimates in the purity of the additives as well as water added during the transfer of feed [64]. An exception is the glass conversion ratio and water content measured for the Test A sample that is well below the target values. The difference in the glass conversion ratio calculated from the total feed processed (224.1 kg, see Table 3.1) and the total glass produced (97.9 kg, see Table 4.1) is only 7%, suggesting a sampling bias. In subsequent tests, more feed samples were taken during each test to better distinguish such sampling biases. In all but the AN-107 (Sub-Envelope C1) waste, the measured pH is higher in the samples from the current tests since much of the additional sodium is introduced to the feed as sodium hydroxide. Measured feed densities and feed solids content in the current tests are similar to those measured in previous tests with the same wastes except for AZ-102 (Sub-Envelope B2 waste), in which the samples from the current tests have higher solids content.

2.6.2 Chemical Composition

The chemical compositions of the feed samples were determined by first making a glass from the feed sample via crucible melt. The glass was subsequently crushed and analyzed directly by XRF. The boron and lithium oxide target values were used for normalizing the XRF data since their concentration was not determined by XRF. The XRF-analyzed compositions of the feed samples are provided in Table 2.42. The results generally show good agreement with the target composition for the major components. Of the oxides with target concentrations of one percent or greater, the XRF values had deviations of less than 10% except for vanadium and tin, which had a high bias between 8 and 14.34 percent, zirconium which deviated in some samples due presumably to settling in the feed tank or sampling container, and calcium in the Test A feed. The deviations in tin and vanadium were also observed in the product glasses and may be attributable to a potential analytical bias for these elements using XRF [2, 6, 7, 64] (see Section 4.1). The surplus in calcium observed in the feed sample was not observed in the product glass and therefore is likely attributable to sampling deviations.

A surplus of sodium was observed in the feed samples as well as the product glasses from Tests D1 – D4. Although the sodium surplus was less than ten relative percent, the absolute surplus of sodium was on the order of one weight percent oxide, which has the potential to degrade the chemical durability of the product glass. A source of feed contamination was identified and Test D4 was repeated with new chemicals as Test D5.

Volatile minor elements such as sulfur and chlorine are, as expected, below target due to loss during crucible melting. In samples taken prior to the addition of sulfur, small amounts of sulfur were measured in the feed as a contaminant and indicate a lower bound on the amount of sulfur in that feed since an indeterminate amount is volatilized during crucible melting. The amount of sulfur contamination in the feed was not taken into account in the amount of sodium sulfate added to the feed and therefore the actual amount in the feed may be slightly over the target concentration. The amount of sulfur in the feed, which is important for determining sulfur retention in the glass, is assumed to be the target concentration; the target is calculated, checked, and the corresponding amounts of chemicals are weighed out using calibrated balances. Titanium oxide was measured in the feed samples from one to three tenths of a weight percent, even though it was not included in the target composition. Similar observations were made in previous tests with LAW melter feeds [7, 10, 11, 17-19, 64] and is due to its presence as a contaminant in the glass forming additives, most notably kyanite [2]. Iodine was measured in the feed samples at around a tenth of a weight percent as a result of its presence as an impurity in the tin additive used. Common elements such as chromium, iron, and phosphorus, which are typical impurities in bulk chemicals, are over-represented when the constituent is a minor component. Higher measured concentrations for these common elements may also be attributable to uncertainties at these low concentrations.

SECTION 3.0 DM10 TESTS

Melter tests were conducted on the DM10 with the LAW simulants from 10/15/08 to 10/23/08 and 1/5/09 to 1/16/09 to determine the maximum sulfur concentration that can be processed without forming secondary phases for each of the four compositional regions. These tests produced almost half a metric ton of glass from about a metric ton of feed. Tables 3.1 - 3.4 provide summaries of the DM10 tests, including run times, the amount of sulfur in the feed, the amount of feed processed, the amount of feed sulfur retained in the glass product, observations of secondary phases, key processing parameters, and measured concentrations of gaseous species. The tests, listed in the order in which they were performed, were as follows:

- Test A: Four nominally 14-hour feeding segments with LAW ORP S8AN105 simulated wastes with a Na₂O concentration of 24 wt% in the ORPLA20 target glass composition. Segments tested SO₃ concentrations of 0.5, 0.7, 0.8, and 0.9 wt% in the glass product (assuming total retention).
- Test D: Five nominally 14-hour feeding segments with LAW ORP S8AN102 simulated wastes with a Na₂O concentration of 22 wt% in the ORPLD6 target glass composition. Segments tested SO₃ concentrations of 0.9, 1.1, 1.2, and 1.3 wt% in the glass product (assuming total retention). The sulfur concentration of 1.2 wt% SO₃ was tested a second time with a corrected sodium content.
- Test F: Six nominally 14-hour feeding segments with LAW ORP S5AZ102 simulated wastes with a Na₂O concentration of 12 wt% in the ORPLF7 target glass composition. Segments tested SO₃ concentrations of 0.8, 1.2, 1.4, 1.5 and 1.6 wt% in the glass product (assuming total retention). The sulfur concentration of 1.4 wt% SO₃ was tested a second time to add additional confidence to the results.
- Test G: Three nominally 14-hour feeding segments with LAW ORP S8AP101 simulated wastes with a Na₂O concentration of 21 wt% in the ORPLG9 target glass composition. Segments tested SO₃ concentrations of 0.2, 0.4, and 0.5 wt% in the glass product (assuming total retention).

The principal objective of these tests was to determine, for each feed, the maximum amount of sulfur that can be fed into the melter without forming secondary sulfate phases. The bubbling rate was adjusted to maintain target glass production rates between 2250 and 2500 kg/m²/day with a complete cold cap. Test segment durations of 12 to 17 hours were selected since, at the target glass production rate, this provided three melt pool turnovers (24 kg) for each sulfur concentration. Sugar was added to the feed at a stoichiometric carbon ratio of 0.5 for all of the melter tests. At the end of each test segment, dip samples were taken to detect the presence of a separate sulfur phase on the glass pool surface. The melt surface was considered free of a sulfate layer if no visible secondary sulfate phases were observed on any of the three dip

samples. If a sulfate layer was detected on the melt surface, the glass pool was bubbled until the dip samples indicated that the sulfate layer had dissipated prior to commencing the subsequent test segment.

3.1 DM10 System Description

3.1.1 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 through a peristaltic pump into the melter through a Teflon-lined feed line and vertical water-cooled feed tube. A diverter valve permits direction of the feed stream either to the melter or to a sampling vessel.

3.1.2 Melter

The DM10 system used for this work is a ceramic refractory lined melter, which includes two Inconel 690 plate electrodes that are used for joule-heating of the glass pool and a bubbler for agitating the melt. Glass is discharged from the melter using an air-lift system. The melt pool has a surface area of 0.021 m² and typically contains about 8 kg of glass. The plenum volume is 19.5 liters at the nominal glass level. Inconel 690 thermowells were custom fabricated and installed in the DM10 for the current tests since in previous tests, thermowells made from Inconel 601 experienced rapid corrosion in tests with high-alkali, high-sulfur feeds [5].

3.1.3 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. The geometry of the transition line (between the melter and the first filtration device) 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. The sampling location for gaseous species monitored by FTIR is immediately downstream of the draft fan.

3.2 DM10 Test Conditions

Target processing conditions, including bubbling rate adjusted to maintain a target production rate between 2250 and 2500 kg/m²/day, a melt pool temperature of 1150°C, and a complete cold cap were achieved throughout the majority of the melter tests. Test segment average production rates ranged from 1950 to 2678 kg/m²/day. The target rate could not be reached in the last two segments of Test G due to foaming of the glass. Similar problems were observed in previous DM10 tests with LAW wastes which used tin and vanadium as additives at oxide concentrations greater than one and a half weight percent and relatively high melt viscosity [7]. Test segment average bubbling rates ranged from 1.8 to 4.1 liters per minute and were generally lower while processing the ORPLF7 (Test F) and ORPLG9 (Test G) glass formulations, the latter of which resulted from attempts to limit foaming.

The measured test segment average glass temperatures two inches from the melt pool floor were between 1151 - 1159°C for all test segments, thus indicating that the target glass temperature of 1150°C was achieved. Measured glass temperatures two inches higher in the glass pool were 4 to 40°C lower throughout testing due to the proximity to the glass surface. Average temperatures during test segment D3 were lower due to power being lost to the melter for about 2 hours (feeding was also discontinued during this period). Each test segment started with the melt pool at the nominal operating temperature of 1150°C. Typical plots of DM10 melter temperatures are given in Figures 3.1.a and 3.1.b. The plots are for the first and the last complete tests (Tests A and G). As mentioned above, the data at 2" from the melter bottom are most representative of the bulk glass temperature; these data average very close to the target of 1150°C and vary little during feeding periods. The measurement 4" from the bottom is closer to the melt surface and varies by about 80°C as the level of the glass changes. Variations in temperatures measured at both locations were observed during idling periods used to take glass dip samples and purge the melt surface of secondary sulfate phases. In keeping with previous DM10 tests, the electrode temperatures were lower than glass pool temperatures; however, the difference was about half the 50 to 100°C difference observed in the previous tests. The measured test segment average plenum temperatures were well below 600°C, indicating that a complete cold cap covered the melt pool surface throughout the tests. Typical plots of DM10 plenum temperatures are given in Figures 3.2.a and 3.2.b for the first and last complete tests conducted. Higher plenum temperatures occurred at the beginning of testing and in between test segments while the melt pool was probed for secondary sulfate phases. Unlike plenum temperature measurements on larger melters, the exposed thermocouple often gave a lower temperature reading than the thermocouple in the thermowell due to variable amounts of feed coating the exposed thermocouple.

3.3 DM10 Test Results

Evaluation of glass pool samples provided an indication of the tolerance of the glass formulations to sulfur at nominal melter conditions. Depictions of the target and measured sulfur contents are provided in Figures 3.3.a – 3.3.d for each of the test series. During Test A with the

ORPLA20 target glass composition, secondary sulfate phases were observed while processing feeds targeted at 0.8 and 0.9 wt% SO₃ but not at 0.5 and 0.7 wt% SO₃; thus the sulfur saturation occurs between 0.7 and 0.8 wt% SO₃.

The second test series conducted with ORPLD6 target glass composition show increases in the feed and glass sulfur concentrations to a feed sulfur concentration of 1.3 wt% SO₃ where a secondary sulfate phase was observed. A following test segment conducted with SO₃ feed concentration of 1.2 wt% resulted in no secondary sulfate phases; however, subsequent analysis of the glass indicated the sodium concentration of the Test D product glasses was higher than targeted (see Section 4.2 and 4.4). Therefore, after conducting several other tests with the other glass compositions, this test was repeated using feed with the proper sodium concentration and 1.2 wt% SO₃; that test showed the presence of a secondary sulfate phase. The apparent contradiction of results indicates that this glass composition is near saturation at 1.2 wt% SO₃ and that subtle change in concentration or transitions in the glass pool can result in secondary sulfate phases.

Secondary sulfate phases were conspicuous after the first segment of Test F with feed containing 1.6 wt% SO₃ but not in subsequent segments. A trace amount of secondary sulfate was observed after processing 1.4 wt% SO₃; however, since no secondary phases were observed after subsequent tests processing 1.4 and 1.5 wt% SO₃, the trace amount of sulfate observed after the second test segment was probably transient. The tolerance of the ORPLF7 target glass composition is therefore between 1.5 and 1.6 wt% SO₃ in the feed.

The most extensive secondary phases were observed during Test G with the ORPLG9 target glass composition. Secondary sulfate phases were observed at the end of each test segment, even as the sulfur content of the feed was reduced from 0.5 to 0.2 wt% SO₃, indicating that this glass formulation has little tolerance for sulfur. The potential reasons for the very low sulfate tolerance of the ORPLG9 feed are discussed in Section 4.3.

3.4 Gases Monitored by FTIR

Melter emissions were monitored in each test for a variety of gaseous components, most notably carbon monoxide, ammonia, sulfur dioxide 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 in order to prevent analyte loss due to condensation prior to monitoring. Test segment average concentrations of NO, NO₂, CO, and NH₃ are provided in Tables 3.1-3.4; these analytes are those that were expected to be observed during the test, based on previous work. No SO₂ was detected in any of the tests and therefore none is reported in the tabular data. The FTIR detection limit for sulfur dioxide is relatively high (5 ppmv) and, therefore, measurable quantities are only observed with high sulfur containing feeds and in systems with minimal dilution of the melter exhaust by film cooler or process air. The most abundant nitrogen species monitored was NO, which is consistent with previous tests [2-7, 10, 11, 18-27, 43] in which nitrates and nitrites were abundant in the feed. The measured concentrations of most monitored components increase with increasing feed nitrogen oxide

content and feed rates. Nitrogen oxide, carbon monoxide, and ammonia concentrations are significantly lower during Test F with the feed containing LAW AZ-102 simulant, as a result of the low nitrate and consequently lower organic content in the feed.

SECTION 4.0 DM10 GLASS PRODUCTS

Almost half a metric ton of glass was produced in these tests. The glass was discharged from the melter periodically into square steel cans using an airlift system. The discharged product glass was sampled at the end of each test by removing sufficient glass from the top of the cans for total inorganic analysis. Care was exercised during sampling of each can to identify and segregate any potential secondary phases; however, no secondary phases were observed in the discharged glass. Product glass masses, discharge date, and analysis performed are listed in Table 4.1. Glass samples were also obtained by dipping a rod into the glass pool at the beginning and end of each test. These "dip samples" underwent visual examination to detect the presence of a separate sulfate phase on the glass pool surface.

4.1 Compositional Analysis

Glass discharge samples were crushed and analyzed directly by XRF. The target values for boron and lithium oxides, which are not determined by XRF, were used for normalizing the XRF data to 100 wt%. The XRF-analyzed compositions of all discharged glass samples are provided in Tables 4.2. Results of XRF analysis of glass samples are compared with the target composition and results of DCP analysis of solutions generated by microwave aided acid dissolution in Tables 4.3 and 4.4, respectively. Samples were selected for this comparison from the end of tests with the highest sulfur concentrations without forming secondary phases on the melt pool surface, and from multiple test segments if the test segments for a given composition were not conducted consecutively. The majority of the XRF analysis results compare favorably to their corresponding target values and feed sample analysis (see Section 2.6.2). The concentrations of vanadium oxide were 10 to 13 relative percent above target concentrations. In all but one analysis (for tin), the concentrations of chromium, tin, and vanadium measured by the DCP method were closer to target values, suggesting that the XRF may have a high bias for these elements. Above target concentrations of vanadium were also measured in previous tests [2, 6, 7, 64]. Similar to the feed samples, zirconium oxide concentrations were up to fifteen relative percent below target concentrations, due presumably to chemical purity or settling of zircon crystals in the feed tank. Iron oxide concentrations were above the low target concentrations due to the ubiquity of the element in bulk chemicals. Elements not included in the target glass compositions, including iodine, manganese, nickel, lead, phosphorus, titanium, tin, and vanadium were observed in the product analysis as a result of corrosion of melter components, carry-over from previous tests, and trace contamination of additives.

The higher than target concentration of sodium observed in the feed samples from Test Segments D1-D4 (see Section 2.6.2) is also observed in the glass product. The surplus in these samples of about one and a third absolute percent is not present in glass samples from Test Segment D5 after a new batch of chemicals was used in feed formulation. Measured boron and

lithium concentrations were within five percent of the target, validating the use of the target value for normalizing the XRF data. Agreement between the two analytical methods was excellent, except for low sodium values obtained from the DCP analysis, which is due in part to a low-bias for sodium [6, 64]; previous experience indicates that the XRF results are more reliable in this regard. Also silicon results are lower by the DCP method due perhaps to its incomplete dissolution during sample preparation.

Compositional trends of the major and select oxides during the tests are shown in Figures 4.1.a. - 4.8.b. They illustrate the differences between the tested compositions and closeness to target over the course of the tests. These depictions also show the sampling and analytical variations attributable to the methods used; for example, potassium shows minimal variability whereas zirconium can vary by about half a weight percent in sequential glass discharges. Discontinuities are readily observed in the changes in sulfur, calcium, zirconium, magnesium, and potassium between the fourth and fifth segments for Tests D and F as a result of the latter segments being conducted after processing several other compositions during the intervening interval. The glass compositions were held constant during each testing sequence and therefore the most significant changes were observed during the first test segment. These changes for additives calcium, magnesium, vanadium, and tin as well as the waste components sodium, potassium, and chlorine are evident in the plotted data.

As intended, sodium spanned a range of twelve weight percent oxide, which was greater than for any other element. The plotted sodium data show a close approximation to target for four of the compositions with small deficiencies during Test A and a small excess of sodium during the first four segments of Test D, which was remedied in the fifth segment by using new batches of reagents. High analytical bias is shown for the additives vanadium and tin as well as deficiencies in aluminum and zirconium in some tests are observed in the plotted data. Chlorine loss during these tests was 15 to 30%, which is less than the near-50% loss of chlorine from the glass at target concentrations greater than 0.3 weight percent [7, 25, 52] found in previous tests. This difference may be due to the higher concentration of sodium in the target glasses and possibly higher chlorine contamination of feed constituents. Complete sampling and analysis of melter exhaust commonly conducted on larger melters [2-6, 10, 11, 18-27, 61-63, 65] is required for a more accurate assessment of elemental volatility and mass balance calculations. Measured chromium oxide concentrations were about 0.25 weight percent above target concentrations during Tests A, D, and F, and about 0.3 weight percent above target during Test G. Surpluses of chromium in the feed were about 0.2 weight percent for feed samples from Tests A and F, and 0.12 weight percent for feed samples from Tests D and G. The difference between the feed and product glass concentration indicates that about 0.12 weight percent chromium oxide during Test D and 0.2 weight percent chromium oxide during Test G can be attributed to corrosion of melter brick and Inconel components.

4.2 Secondary Phase Observations

All discharged glass and glass “dip” samples taken directly from the melt pool were closely examined to document the presence or absence of secondary phases. Glass dip samples

were obtained from three separate locations in the melt pool at the end of each test segment; these samples were collected to ascertain whether a secondary sulfate layer had formed on the surface of the glass melt in response to the feed sulfur concentration used for that test segment. Samples were also taken to ensure the melt surface was free of secondary phases prior to starting each test segment, as well as after bubbling intended to volatilize sulfur from a previously formed sulfur layer. Table 4.5 provides a listing of all of the dip samples and whether or not a separate salt phase was evident. Examples of secondary phases observed while processing three of the formulations are shown in Figures 4.9 – 4.11. Notice the powdery yellow material adhering to the rod and interspersed throughout some of the glass, both of which are indicative of a sample taken from a melt pool with a sulfate layer on the surface. Some of the sulfur layers that formed on the glass pool surface were extensive. Several hours of melt pool bubbling, and in some instances water feeding, were required to rid the melt pool of secondary phases.

4.3 Comparison of the Properties of Crucible and Melter Glasses

Samples of DM10 discharge glasses and crucible melts for each waste composition were subjected to the PCT leaching procedure. When possible, samples were collected from melter test segments during which the highest sulfate concentrations that did not result in secondary sulfate phases were processed. The PCT releases of the melter glasses, along with those of crucible glasses with the same target compositions, are given in Table 4.6 and compared in Figure 4.12. PCT releases of all of the melter and crucible glasses are well below the WTP contract limit mass loss of 2.0 g/m² for B, Na and Si. The PCT results for melter and crucible glasses are similar, with the differences within expected variations based on round robin PCT testing of an Argonne National Laboratory-Low Activity Reference Material (ANL-LRM) glass sample [66].

VHT results for the melter and corresponding crucible glasses with the same target composition are given in Table 4.7. VHT alteration rates calculated by two different methods are given in Table 4.7. One method involves direct measurement of the alteration layer thickness, while the other involves measurement of the remaining glass. The VSL Standard Operating Procedure (SOP) for VHT measurement specifies that when the alteration layer thickness is greater than 100 µm, it should be determined based on the remaining glass. This is because when the alteration layer thickness is sufficiently large, measuring the dimensions of the remaining glass and subtracting it from the original sample dimensions gives a better estimate of the thickness of the altered layer. A direct measurement of the layer thickness can provide erroneous values because the altered layer may have expanded, thus giving a larger value than the actual thickness of the altered part of the glass sample, particularly for thick layers. The VHT alteration rates given in Section 2 are mostly based on the measurement of the remaining glass. The VHT alteration rates for the melter glass samples are all higher than those for the corresponding crucible melt samples. One of the reasons for the difference is the presence of bubbles and cracks in the melter glass samples, which are absent in the crucible glass samples. Excessive alteration around bubbles and cracks in melter glass samples as compared to the crucible glasses can be seen in Figures 4.13 to 4.16. Another potential reason is that the melter glasses prepared from slurry feeds are likely to contain more OH groups in the structure as compared to the crucible

melts prepared from dry chemicals, which would also likely lead to higher VHT alteration rates. All but one of the samples showed VHT alteration rates that are less than the WTP contract limit of 50 g/m²/day. The exception is for the VHT coupon of the melter glass sample 10A-G-43B, with the ORPLG9 composition, which was almost completely altered. As is evident from Figure 4.16b, bubbles and cracks in this melter glass sample clearly increased the VHT alteration. The fact that the ORPLG9 melter glass sample failed the VHT alteration rate limit of 50 g/m²/day is not surprising because the crucible melt sample of the ORPLG9 composition showed a VHT alteration rate in the range of 41-50 g/m²/day and the uncertainty associated with VHT measurements is about $\pm 31\%$ [60].

The densities of both the as-discharged glass samples and remelted samples were also measured. Some of the discharge glass samples contained gas bubbles and therefore density measurements were made on the as-discharged and remelted samples in order to get an estimate of the amount of bubbles in the as-discharged glasses. The remelted glass samples were almost free of bubbles. The results of the measurements are given in Figure 4.17. As can be seen in the figure, ORPLG9 glass contained the most bubbles, with lesser amounts in ORPLA20 and ORPLD6, and the least in ORPLF7. The measured densities are all below the limit of 3.7 g/cc. The largest difference in density between the as-discharged and remelted melter glass samples was for the ORPLG9 composition, where the density of the remelted glass sample was about 5% higher than that of the as-discharged sample.

SECTION 5.0 SUMMARY AND CONCLUSIONS

Several tests were conducted on the DM10 vitrification system to evaluate newly developed LAW glass formulations intended to maximize waste loading. Glass formulations for the melter tests were selected on the basis of a series of crucible melts that were prepared and characterized. Glasses were formulated for four different waste streams, maximizing sodium content at progressively higher target sulfur contents while meeting requirements for product quality (PCT and VHT), refractory corrosion characteristics, and processing properties. The results from this work, in combination with our previous work in this area, provides ORP with a broad basis of glass formulation and characterization data from which to assess the likely enhancements in LAW loadings that should be possible in the WTP LAW design with the current product quality and processability constraints. Such enhancements provide the potential for significant cost and schedule savings. Implications of the results from this work for the WTP and recommendations for future work are provided at the end of this section.

The GFC additives that have been used previously in the LAW glasses are Al_2O_3 , B_2O_3 , CaO , Cr_2O_3 , Fe_2O_3 , Li_2O , MgO , SiO_2 , SnO_2 , TiO_2 , V_2O_5 , ZnO and ZrO_2 . For the present work, Fe_2O_3 and TiO_2 were not used as glass former additives, instead focusing on SnO_2 and V_2O_5 additions to improve waste loadings while maintaining acceptable glass properties. ZnO is added at concentrations in the range of 2 to 3 wt% mainly to reduce corrosion of K-3 refractory by the glass. It is also beneficial in reducing corrosion of Inconel components. MgO and Fe_2O_3 were previously added to reduce K-3 corrosion and as an allowance for their presence as impurities in other GFCs. In the present work, Fe_2O_3 was not used as a glass former additive, and a number of glasses were formulated without either Fe_2O_3 or MgO , so that Fe_2O_3 as an impurity from the MgO source, olivine, can also be avoided. From the test results, it is not clear whether removal of Fe_2O_3 and/or MgO adversely affected K-3 refractory corrosion, but refractory corrosion was a significant issue for the high-waste-loading, high-alkali formulations. In general, components such as SiO_2 , SnO_2 , and ZrO_2 improve the chemical durability of the glass, including performance on the PCT and VHT. Of these, ZrO_2 and SnO_2 are the most effective in reducing VHT alteration rates. These components usually are also effective in reducing corrosion of both K-3 and Inconel by the glass. Even though Al_2O_3 , in general, tends to improve chemical durability, its substitution by other components such as SiO_2 , SnO_2 , and ZrO_2 can be beneficial in reducing VHT alteration rates. Increases in B_2O_3 concentration can have variable effects on chemical durability and typically tend to reduce melt viscosity. Li_2O , CaO , and V_2O_5 all are beneficial in increasing sulfate loading, with Li_2O being the most effective. In general, as very high sodium glasses are formulated, the concentrations of components that reduce corrosion and improve chemical durability need to be increased. In addition, these components typically increase the viscosity of the glass melt. As relatively lower sodium and higher sulfate glasses are formulated, the concentrations of additives that increase sulfate solubility are increased. Cr_2O_3 is added solely to reduce corrosion of K-3 refractory by the glass. The addition of Cr_2O_3 has been quite successful in increasing the waste loading in high alkali LAW glasses, where K-3 refractory corrosion can limit waste loading. However, it is also known that sulfate and chromate show synergistic behavior [67] and the presence of chromium can increase the tendency for secondary sulfate/chromate phase formation, which can potentially limit waste loading in LAW

glasses that contain sulfur. We believe that this effect was observed in at least one of the glasses tested, ORPLG9, as discussed below. It should be noted that the effect of the addition of each of these components cannot be taken in isolation. Each has to be considered in combination with the other glass former additives, the overall composition of the glass, and relevant glass melt properties such as viscosity and glass redox state. For the current work, glass formulation development and testing were designed such that the maximum achievable waste loadings could be determined for four LAW streams specified by ORP. Details of the LAW glasses selected for the current set of melter tests for the four regions, ORPLA20, ORPLD6, ORPLF7, and ORPLG9, are summarized below.

ORPLA20: The glass formulation development for Region A was based on the composition of LAW from Hanford tank AN-105. The developed glass formulation, ORPLA20, has a target waste loading of 31.6 wt%, with target Na₂O and SO₃ loadings of 24.0 and 0.7 wt%, respectively. The waste loading for the previous ORP glass developed for this LAW stream, ORPLA15 [7], had the same Na₂O and overall waste loadings, but a lower SO₃ loading of 0.6 wt%. In addition, ORPLA20 shows much improved performance on the VHT as compared to ORPLA15, which was achieved by the addition of SnO₂ in place of Fe₂O₃, and substitution of part of the Al₂O₃ additive with SiO₂. The waste loading of 31.6 wt% in ORPLA20 is higher than that in the corresponding WTP LAW correlation glass, LAWE4H [52] of 27.2 wt%, and the WTP LAW baseline glass, LAWA44 [13] of 26.0 wt%. The nominal composition of LAW from tank AN-105 has a SO₄/Na molar ratio of 3.0×10^{-3} , which equates to an SO₃ concentration of 0.18 wt% at a Na₂O loading of 24.0 wt%. Glass ORPLA20, which can accommodate 0.7 wt% SO₃ at 24.0 wt% Na₂O loading can, therefore, be used to treat LAW AN-105 type streams with SO₄/Na ratios of up to 1.16×10^{-2} .

ORPLD6: The glass formulation development for Region D was based on the composition of LAW from Hanford tank AN-102. The developed glass formulation, ORPLD6, has a target waste loading of 25.9 wt%, with target Na₂O and SO₃ loadings of 22.0 and 1.2 wt%, respectively. The waste loading for the previous ORP glass developed for this LAW stream, ORPLD1 [7], had a target waste loading of 24.9 wt%, with target Na₂O and SO₃ loadings of 21.0 and 1.1 wt%, respectively. Compared to ORPLD1, ORPLD6 has slightly higher (but still safely below the limit) VHT alteration rate and shows higher K-3 refractory corrosion. The waste loading improvement was obtained through increases in the concentrations of ZrO₂ and V₂O₅ and decreases in B₂O₃ and Fe₂O₃ in the glass. The waste loading of 25.9 wt% in ORPLD6 is substantially higher than that in the corresponding WTP LAW correlation glass, LAWE7H [52] of 16.2 wt%, and the WTP LAW baseline glass, LAWC35 [13] of 14.0 wt%. The nominal composition of LAW from tank AN-102 has a SO₄/Na molar ratio of 2.1×10^{-2} , which equates to an SO₃ concentration of 1.01 wt% at a Na₂O loading of 22.0 wt%. Glass ORPLD6, which can accommodate 1.2 wt% SO₃ at 24.0 wt% Na₂O loading can, therefore, be used to treat LAW AN-102 type streams with SO₄/Na ratios of up to 2.5×10^{-2} .

ORPLF7: The glass formulation development for Region F was based on the composition of LAW from Hanford tank AZ-102. The developed glass formulation, ORPLF7, has a target waste loading of 14.3 wt%, with target Na₂O and SO₃ loadings of 12.0 and 1.5 wt%, respectively. The waste loading for the previous ORP glass developed for this LAW stream, LAWB99 [6], had a

target waste loading of 11.9 wt%, with target Na₂O and SO₃ loadings of 10.0 and 1.5 wt%, respectively. Another comparable glass is ORPLE12 [7], which was formulated for waste from LAW tank AZ-101, which had Na₂O and SO₃ loadings of 16.0 and 1.5 wt%, respectively. It is interesting to note that all three glasses (LAWB99, ORPLE12 and ORPLF7) had a maximum SO₃ loading of 1.5 wt%, even though the Na₂O concentrations varied from 10.0 to 16.0 wt%. Glasses ORPLE12 and ORPLF7 were formulated with ~0.5 wt% Cr₂O₃ to minimize refractory corrosion, whereas LAWB99 contained only about 0.1 wt% Cr₂O₃ entirely from the waste. These results suggest that 1.5 wt% SO₃ may be a practical limit for sulfur loading in LAW glasses, but there is a possibility that removal of the chromium additive may increase it slightly. It should be noted that LAWB99 was an early ORP glass and improvements in glass formulations since then have increased the capacity for sulfate loading in LAW glasses. In addition, since the K-3 corrosion issue in these glasses is cracking rather than material loss at the neck, glass formulations without Cr₂O₃ addition should be feasible. The waste loading of 14.3 wt% in ORPLF7 is substantially higher than that in the corresponding WTP LAW correlation glass, LAWE10H [52] of 6.2 wt%, and the WTP LAW baseline glass, LAWB96 [13] of 5.5 wt%. The nominal composition of LAW from tank AZ-102 has a SO₄/Na molar ratio of 6.24×10^{-2} , which equates to an SO₃ concentration of 1.93 wt% at a Na₂O loading of 12.0 wt%. Glass ORPLF7, which can accommodate 1.5 wt% SO₃ at 12.0 wt% Na₂O loading can, therefore, be used to treat LAW AZ-102 type streams with SO₄/Na ratios of only up to 4.85×10^{-2} . In addition, blending LAW AZ-102 with other lower sulfur waste streams should allow ORP to reduce the overall amount of LAW glass produced at Hanford.

ORPLG9: The glass formulation development for Region G was based on the composition of LAW from Hanford tank AP-101. In addition to Na₂O and SO₃, this waste has a high concentration of K₂O. The developed glass formulation, ORPLG9, has a target waste loading of 29.1 wt%, with target Na₂O, K₂O and SO₃ loadings of 21.0, 5.8 and 0.2 wt%, respectively. The waste loading of 29.1 wt% in ORPLG9 is higher than that in the corresponding WTP LAW correlation glass, LAWE3 [52] of 25.4 wt%, and the WTP LAW baseline glass, LAWA126 [13] of 24.5 wt%. Due to the high alkali content, the properties of concern in glass formulation were VHT alteration rate and K-3 refractory corrosion. To determine processing characteristics of glasses at the limit of acceptable VHT alteration and K-3 corrosion, ORP selected ORPLG9 for DM10 melter tests. In this glass, in order to minimize K-3 corrosion, Cr₂O₃ was kept at a concentration of 0.59 wt%. The measured SO₃ solubility in the crucible glass was 0.48 wt% by batch saturation tests and 0.65 wt% by bubbling. However, during DM10 melter tests, a secondary sulfate layer was found even at the lowest sulfate level of 0.2 wt%. The Cr₂O₃ content in the melter glass was ~1.0 wt% or higher (see Figure 5.2). These observations may be the result of corrosion of the K-3 refractory by the ORPLG9 glass increasing its Cr₂O₃ content, and the interaction of chromate with sulfate causing sulfate phase formation. To understand this behavior further, bubbling tests for sulfate solubility were conducted on ORPLG9 glass samples with 0.59 wt% and 1.0 wt% Cr₂O₃, the results of which are given in Figure 2.6. The sample with 0.59 wt% Cr₂O₃ showed SO₃ solubility of 0.65 wt%, whereas the sample with 1.0 wt% Cr₂O₃ showed SO₃ solubility of 0.55 wt%. More interestingly, the onset of a separate sulfate layer occurred at an SO₃ concentration of 0.31 wt% in the sample with 0.59 wt% Cr₂O₃, and at 0.17 wt% SO₃ in the sample with 1.0 wt% Cr₂O₃. From these results, the increase in Cr₂O₃ concentration clearly increases the tendency for separate salt phase formation in the ORPLG9

glass formulation and this likely was the cause for the low sulfate tolerance of the ORPLG9 melter feed. The strategy of adding Cr_2O_3 to improve K-3 refractory corrosion characteristics of high-alkali LAW glasses has clearly been successful in high-sodium, low-sulfur compositions. However, this strategy has disadvantages when the sulfur concentration is higher because any improvement in alkali loading may be offset by decrease in the sulfur loading. In addition, the presence of high K_2O concentration also may be a contributing factor in the formation of secondary sulfate phase. The behavior of glass systems that simultaneously contain high concentrations of Na_2O , K_2O , SO_3 , and Cr_2O_3 is complex and would benefit from further investigation. Further work is needed to develop new glass formulations that allow higher sulfate loading at the same waste loading, or glass formulations with a lower waste loading to treat the LAW AP-101 type waste streams.

At the very high Na_2O loadings (23 wt% or higher), VHT response becomes especially challenging due to the rapid increase of VHT alteration rate with increasing alkali content, the increased variability in VHT response at high alkali content, and increased VHT alteration rates due to cracking in melter glasses. K-3 refractory corrosion also becomes an issue at very high alkali concentrations. At the low sodium end, a glass formulation, ORPLF7, with 12 wt% Na_2O that can accommodate 1.5 wt% SO_3 was identified. This was the same SO_3 loading limit that was observed in LAWB99 with 10 wt% Na_2O and in ORPLE12 with 16 wt% Na_2O at a nominal melter operating temperature of 1150°C. Achieving significantly higher SO_3 loadings in borosilicate glasses would appear to be unlikely without changing the processing conditions or the processing and/or product quality constraints (e.g., it is a simple matter to achieve higher SO_3 loadings by increasing the contents of Li, Ca, V, etc., but such glasses do not meet VHT and refractory corrosion requirements). Thus, the glasses identified during the current and previous work [7] serve to define the likely limits of possible Na_2O and SO_3 loadings in Hanford LAW glasses that are compliant with the current product quality and processing requirements. Further work is needed to identify a high waste loading glass composition to treat LAW AP-101 type waste streams that contains high concentration of K_2O in addition to Na_2O and SO_3 . It should be noted, however, that these glasses were tested only at the crucible and DM10 melter scales. Additional testing at larger scales is required to confirm the results from smaller scale testing and the results of such testing may result in refinement of these limits. It should also be noted that because of the bounding nature of the formulations (they are deliberately close to the limits of the requirements), practically viable operating points would fall at somewhat lower waste loadings since nominal glass compositions selected for waste processing need to accommodate process variations without adverse effects on processing or product quality. In addition, the corrosion rate of Inconel in these new glass compositions has not been tested. While experience suggests that the adjustments made to the glass compositions to reduce VHT alteration rate and K-3 corrosion, along with the higher viscosity, will also maintain acceptable Inconel corrosion rates, this needs to be confirmed through testing.

5.1 Implications for WTP

VSL and EnergySolutions have previously developed and tested a number of LAW glass formulations for ORP [4-7] and WTP [12-15]. The formulations that were developed to support

the WTP baseline, as distinct from those developed for ORP that were directed towards enhancements to that baseline, were tested at the crucible scale and at various melter scales, including the one-third scale LAW Pilot Melter at *EnergySolutions*. As a result of the considerable testing completed with the WTP baseline formulations, there is high confidence that they can be used to process LAW at Hanford with little additional testing. The recommended glass compositions for LAW processing were selected such that they can tolerate process variations without adverse effects on processing or product quality. Based on these well-tested formulations, VSL developed a LAW glass formulation correlation that is currently being used by the WTP [40]. Compositions produced by this correlation fall along the dotted lines in Figure 5.1. The WTP baseline formulations were developed to comply with the requirements of the Bechtel contract with ORP [54]. Although these formulations are fully compliant, extensive further optimization with respect to waste loading could not be performed due to the schedule constraints imposed by the LAW Pilot Melter testing program defined by the WTP Project. As a result, while this extensive basis set of formulations provides a solid underpinning of the WTP baseline, there is also potential for improvement of waste loadings. Exploiting this potential has been the subject of the present and previous work for ORP.

LAW testing for ORP at VSL and *EnergySolutions* was aimed at optimizing the glass formulations and processing parameters in order to minimize the volume of glass produced and to shorten the plant operating schedule. An important objective was to determine the likely limits of LAW loading across the full range of expected LAW compositions. Since the major waste loading limiting constituents in Hanford LAW are sodium and sulfur, glass formulation development and testing were focused on maximizing the incorporation of these components in the glass. Target and measured Na_2O and SO_3 concentrations in current and previous ORP LAW glasses for the same LAW streams are given in Table 5.1. A more extensive compilation of the target sodium, potassium, sulfur, and overall waste loading achieved for the four glass compositions from the present work and previous glasses developed for ORP and WTP are given in Table 5.2. An overview of the Na_2O and SO_3 loadings for the WTP and ORP glasses is given in Figure 5.1. As is evident from Figure 5.1 and Table 5.2, these glasses represent considerable increases in waste loadings over the WTP baseline and therefore considerable potential for reductions in cost and schedule. The principal objective of the present work was to assess the likely limits to the extent of this improvement for four LAW streams specified by ORP. Results from the present work combined with previous work for ORP [5-7], show the potential for a 58% increase in average Na_2O loading in Hanford LAW glasses from the WTP baseline of approximately 13 wt% to about 20.6 wt%. This increase in waste loading has the potential to reduce the amount of LAW glass produced at Hanford by about 230,000 MT depending on the amount of process sodium additions. Importantly, these enhancements should be directly applicable to the planned supplemental treatment facility, which is now anticipated to be a second LAW plant. Furthermore, since the approach adopted in the present work was to span likely extremes in the expected LAW compositions, the results would remain relevant if various LAW tank wastes are blended, since blending generally has the effect of affording yet further improvements in waste loadings.

5.2 Recommendations for Future work

The glass formulation developed in this work for LAW AP-101, ORPLG9, has a target waste loading of 29.1 wt%, with target Na₂O and K₂O loadings of 21.0 and 5.8 wt%, respectively. However, the SO₃ loading in this glass is only about 0.2 wt%. The low sulfur tolerance of this glass formulation was partly a result of Cr₂O₃ addition to reduce K-3 refractory corrosion, but the chromium introduced via refractory corrosion may also have been a contributing factor. Further work is needed to better understand this behavior and to develop new glass formulations that allow higher sulfate loading at the same waste loading, or glass formulations with a lower waste loading to treat the LAW AP-101 type waste streams.

In much of the earlier high-alkali LAW glass development work, VHT response was the most constraining property. However, as the database for VHT response for high-alkali LAW glasses has grown and the performance of the VHT model in the composition region has improved [60], there have been corresponding increases in waste loadings for high-alkali glasses with acceptable VHT response. As a result, the present work indicates that K-3 refractory corrosion is now at least as constraining as VHT response for high-alkali LAW glasses. Consequently, more data on this important property and models for K-3 corrosion would be useful.

As discussed before, the high sulfate LAW formulations (LAWB99, ORPLE12 and ORPLF7) all show sulfate loading of 1.5 wt%, even though the sodium loadings vary from 10 to 16 wt%. Two of the three glasses (ORPLE12 and ORPLF7) contain Cr₂O₃ as an additive. It would be useful to determine whether sulfate loading in these glasses can be improved if Cr₂O₃ is not used as an additive.

It is also worth noting that bubbles and cracks that are present in melter glass samples can have significant effects on the measured VHT response, with the result that the measured effects may not necessarily be related solely to the glass composition. This appears to be particularly important for high-alkali glasses with VHT response near the WTP contract limit. More meaningful (or at least more consistent) results would likely be obtained with samples that are remelted to remove the bubbles.

The LAW correlation was developed for the WTP by VSL/EnergySolutions to determine the types and amounts of glass forming chemicals (GFCs) to be used at the WTP for LAW processing under the current WTP baseline. This was possible only after the completion of much more extensive testing than has been done for the new ORP glasses and after a set of nominal Sub-Envelope formulations were refined. The data collected so far for the ORP higher waste loading glasses is not yet sufficiently extensive to support a revised LAW correlation algorithm, but does serve to define what ranges of enhanced waste loadings should be possible. However, once sufficient data are collected, a new LAW formulation correlation similar to the one currently being used by the WTP needs to be developed to support the implementation of these

higher waste loading glass compositions at the WTP in order to realize the cost and schedule reductions. The steps needed to collect the data to support a new LAW correlation include:

- Define GFC additives to be used at the WTP.
- Refine LAW glass formulations using the specified GFC additives.
- Develop new high waste loading glass formulation for AP-101 type LAW with high concentrations of Na, K and S.
- Refine waste loading in LAW glasses to accommodate the effect of halides.
- Specify waste loading limits for LAW formulations to accommodate process variations.
- Perform scale-up testing (DM100 and/or DM1200).

Since the process for producing such a revised correlation would closely parallel the one used successfully to develop the current WTP baseline, there is high confidence in the success of this approach.

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Table 1.1. Waste Compositions and Corresponding Target Concentrations in Glass.

Region Designation	Tank Waste/ Sub-Envelope Identification	Based on Correlation Formulation	Target Minimum Waste Loading, wt%
A	AN-105/ Sub-Envelope A1	LAWE4H	27.18
D	AN-102/ Sub-Envelope C2	LAWE7H	16.22
F	AZ-101/ Sub-Envelope B2	LAWE10H	6.20
G	AP-101/ Sub-Envelope A2	LAWE3	25.41

Table 2.1. LAW Sub-Envelope A1 for AN-105 Waste Simulant Recipe at Nominal 8 Molar Sodium.

Envelope Constituents	Simulant for AN-105 including pretreatment		Glass Oxides	AN-105 Simulant as Oxides (wt%)	Source in Simulant	Order for Addition	Formula Weight	Assay*	Target Weight (g)
-	mg/L	M	Loading		In 274 ml water add following compounds in the order listed below				
Al	30554	1.132	Al ₂ O ₃	17.99	Al(NO ₃) ₃ ·9H ₂ O, 60% sol.	1	375.14	0.61	422.01
					Al(OH) ₃	7	78.00	1.00	35.22
B	79	0.007	B ₂ O ₃	0.08	H ₃ BO ₃	2	61.83	0.99	0.45
Cr	149	0.003	Cr ₂ O ₃	0.07	Na ₂ CrO ₄ ·4H ₂ O	6	234.04	0.99	0.68
K	4608	0.118	K ₂ O	1.73	KOH	5	56.10	0.91	7.28
Na	183920	8.000	Na ₂ O	77.25	NaOH, 50% sol. d=1.53	4	40.00	0.50	463.20
Si	157	0.006	SiO ₂	0.10	SiO ₂	3	60.09	0.99	0.34
Cl	6996	0.065	Cl	2.18	NaCl	8	58.45	0.99	11.65
F	35	0.048	F	0.01	NaF	9	42.00	0.99	0.08
SO ₄ (Nominal) ^{\$}	2274	0.024	SO ₃	0.59	Na ₂ SO ₄	10	142.06	0.99	3.40 ^{\$}
NO ₂	85428	1.857	-	-	NaNO ₂	14	69.00	0.97	128.79
NO ₃	126988	2.048	-	-	NaNO ₃	-	84.99	0.99	0.00
TOC	2093	0.174	-	-	-	-	-	-	-
Acetate	2251	0.038	-	-	Sodium Acetate (C2)	11	136.08	0.99	5.24
Formate	2135	0.047	-	-	Sodium Formate (C1)	12	68.01	0.99	3.26
Glycolate	1936	0.025	-	-	Glycolic Acid (C2)	13	76.05	0.71	2.73
-	-	-	SUM	100.00	Total simulant wt.				1358.73

"-" Empty data field.

* Assay refers to the purity of the raw material as specified by the vendor.

^{\$} SO₃ content varied during each run, as given in Table 2.10b. The value given here corresponds to the nominal.

Table 2.2. Target and Analyzed Compositions (wt%) of Eight ORPLA Crucible Glasses.

GLASS	ORPLA18		ORPLA19		ORPLA20		ORPLA21	
Oxides	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*
Al ₂ O ₃	9.70	9.41	9.70	9.22	6.70	6.40	6.91	6.75
B ₂ O ₃	8.80	9.23	8.80	9.18	8.80	9.34	8.64	8.76
CaO	3.34	3.50	3.34	3.50	3.34	3.54	3.28	3.48
Cr ₂ O ₃	0.50	0.64	0.50	0.68	0.50	0.67	0.50	0.63
Fe ₂ O ₃	0.30	0.32	0.30	0.34	0.30	0.33	0.29	0.32
K ₂ O	0.54	0.53	0.54	0.52	0.54	0.52	0.56	0.55
MgO	0.93	0.83	0.93	0.83	0.93	0.81	0.91	0.94
Na ₂ O	24.00	23.58	24.00	23.35	24.00	23.36	25.00	24.33
SiO ₂	39.52	39.35	39.52	39.13	42.51	42.00	41.72	41.85
SnO ₂	2.76	3.12	4.83	5.64	2.76	3.43	2.71	2.91
ZnO	2.76	2.84	2.76	2.92	2.76	2.95	2.71	2.83
ZrO ₂	6.00	5.80	3.93	3.94	6.00	6.05	5.88	5.62
Cl	0.68	0.72	0.68	0.61	0.68	0.60	0.71	0.62
SO ₃	0.18	0.17	0.18	0.17	0.18	0.16	0.19	0.18
SUM	100.0	100.0	100.0	100.0	100.0	100.2	100.0	99.8

* – Analyzed by X-ray fluorescence except for boron which was measured by DCP

Table 2.2. Target and Analyzed Compositions (wt%) of Eight ORPLA Crucible Glasses (continued).

GLASS	ORPLA22		ORPLA23		ORPLA24		ORPLA25	
Oxides	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*
Al ₂ O ₃	9.46	9.24	9.46	9.16	9.34	9.07	9.17	8.81
B ₂ O ₃	8.80	9.30	8.80	9.49	8.55	9.14	8.39	8.13
CaO	3.55	3.64	3.55	3.63	3.52	3.64	3.45	3.60
Cr ₂ O ₃	0.50	0.63	0.50	0.63	0.50	0.61	0.49	0.61
Fe ₂ O ₃	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.54	0.51	0.54	0.51	0.56	0.53	0.58	0.51
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O	24.00	23.63	24.00	23.87	25.00	24.79	26.00	26.10
SiO ₂	40.29	40.72	40.29	39.79	39.70	39.58	39.10	38.85
SnO ₂	3.00	3.19	5.00	5.65	3.00	3.28	3.00	3.30
ZnO	3.00	3.01	3.00	3.05	2.94	2.98	2.89	2.93
ZrO ₂	6.00	5.44	4.00	3.73	6.00	5.64	6.00	5.66
Cl	0.68	0.62	0.68	0.64	0.71	0.74	0.73	0.72
SO ₃	0.18	0.17	0.18	0.17	0.19	0.17	0.20	0.18
SUM	100.0	100.1	100.0	100.3	100.0	100.2	100.0	99.4

* – Analyzed by X-ray fluorescence except for boron which was measured by DCP

Table 2.3. Descriptions of Eight As-Melted and Heat Treated ORPLA Crucible Glasses.

Glass ID	As-melted glass	Glass remelted at 1200°C for 1 hour, heat treated for 20 hours at 950°C, and quenched.
ORPLA18	Clear glass. <<0.1 vol% of small Cr oxide crystals	Clear glass. <0.1 vol% Na-Zr silicate +Sn crystal + many submicron Au-Pt crystals
ORPLA19	Clear glass. <<0.1 vol% of small Cr oxide crystals	Clear glass. <<0.1 vol% Sn Oxide crystal + many submicron Au-Pt crystals
ORPLA20	Clear glass. <<0.1 vol% of small Cr oxide crystals	Clear glass, showing many acicular submicron Au-Pt crystals
ORPLA21	Clear glass. <<0.1 vol% of small Cr oxide crystals	~0.8 vol% large Na-Zr silicate +Sn crystal
ORPLA22	Clear glass. <<0.1 vol% of small Cr oxide crystals	~0.2 vol% large Na-Zr silicate +Sn crystal
ORPLA23	Clear glass. <<0.1 vol% of small Cr oxide crystals	Mostly clear glass. ~0.1 vol% large Na-Zr silicate +Sn crystal
ORPLA24	Clear glass <0.1% tiny Cr oxide crystals	Mostly clear glass. ~0.1 vol% Na-Zr silicate +Sn crystal
ORPLA25	Clear glass <0.1% tiny Cr oxide crystals	Mostly clear glass. ~0.1 vol% Na-Zr silicate +Sn crystal

Table 2.4. Measured Sulfate Solubility Limits in Eight ORPLA Glasses.

Sample ID	SO ₃ Content (wt%)	
	Batch Saturation	
	As-Melted	After Acid Wash
ORPLA18S4	0.31	0.30
ORPLA19S4	0.33	0.32
ORPLA20S4	0.38	0.37
ORPLA21S4	0.40	0.37
ORPLA22S4	0.34	0.33
ORPLA23S4	0.35	0.36
ORPLA24S4	0.36	0.35
ORPLA25S4	0.42	0.41

Table 2.5. Results of 7-day PCT (at 90°C) and VHT (at 200°C for 24 Days) for Eight ORPLA Crucible Glasses.

Glass ID	ORPLA18	ORPLA19	ORPLA20	ORPLA21	ORPLA22	ORPLA23	ORPLA24	ORPLA25
7-Day PCT, Stainless Steel Vessel; S/V=2000m⁻¹ (ppm)								
B	30.34	36.03	39.61	51.06	28.77	24.86	32.10	44.00
Na	206.20	247.50	261.40	350.60	224.70	210.40	274.30	375.80
Si	67.09	81.98	91.43	106.50	66.71	70.49	72.94	85.02
Normalized Concentrations (g/L)								
B	1.11	1.32	1.45	1.90	1.05	0.91	1.21	1.69
Na	1.16	1.39	1.47	1.89	1.26	1.18	1.48	1.95
Si	0.36	0.44	0.46	0.55	0.35	0.37	0.39	0.47
pH	11.67	11.75	11.77	11.95	11.74	11.67	11.7	11.93
7-Day PCT Normalized Mass Loss (g/m²)								
B	0.56	0.66	0.72	0.95	0.53	0.45	0.60	0.84
Na	0.58	0.70	0.73	0.95	0.63	0.59	0.74	0.97
Si	0.18	0.22	0.23	0.27	0.18	0.19	0.20	0.23
7-Day PCT Normalized Loss Rate (g/m²/d)								
B	0.08	0.09	0.10	0.14	0.08	0.06	0.09	0.12
Na	0.08	0.10	0.10	0.14	0.09	0.08	0.11	0.14
Si	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.03
VHT Alteration (24 days at 200°C)								
Alteration Depth (µm)	324	202	65	387	24	109	113	381
Alteration Rate (g/m ² /day)*	36	22	7	43	3	12	12	42

* Alteration rates calculated using estimated density of 2.65 g/cc

Table 2.6. Viscosities and Electrical Conductivities of Three ORPLA Crucible Glasses.

Glass ID	ORPLA18	ORPLA19	ORPLA20
Viscosity (poise)			
900°C	2576	2454	2379
950°C	961	916	872
1000°C	414	393	372
1050°C	200	189	179
1100°C	106	100	95
1150°C	60	57	54
1200°C	37	34	33
1250°C	23	22	21
Electrical Conductivity (S/cm)			
900°C	0.305	0.288	0.209
950°C	0.372	0.351	0.286
1000°C	0.447	0.422	0.373
1050°C	0.530	0.500	0.469
1100°C	0.621	0.585	0.572
1150°C	0.719	0.677	0.681
1200°C	0.824	0.776	0.794
1250°C	0.936	0.881	0.911

Table 2.7. Results of K-3 Corrosion Testing for Four ORPLA Crucible Glasses.

Glass ID	Neck loss (inches)	Depth of altered zone (inches)	Half-down loss (inches)
ORPLA20	0.033	0.027	0.000
ORPLA21	0.061	0.021	Coupon expanded – no measurable loss
ORPLA24	0.064	0.021	0.000
ORPLA25	0.089	0.023	0.000

Table 2.8. Summary of Test Results for Selected ORPLA Glass Formulation ORPLA20 and Comparison to ILAW Requirements.

Test	Requirement [53, 54]	Test Result for ORPLA20
Density of glass	< 3.7 g/cc	2.59 g/cc*
Crystalline Phase	Phase identification	Clear homogeneous glass after heat treatment at 950°C for 20 hours
Liquidus	< 950°C	< 950°C
Centerline Canister Cooling	Phase identification	Not measured
PCT B (g/m ²)	< 2.0 g/m ²	0.72 g/m ²
PCT Na (g/m ²)	< 2.0 g/m ²	0.73 g/m ²
PCT Si (g/m ²)	< 2.0 g/m ²	0.23 g/m ²
VHT at 200°C (g/m ² /day)	< 50 g/m ² /day	7 g/m ² /day
Viscosity (poise) at 1100°C	10 to 150 P	95 P
Conductivity (S/cm) at 1100°C	0.2 to 0.7 S/cm	0.572 S/cm
T _G (°C)	Report for modeling	Not measured

*Density measured for melter glass Y10-G-146C of the ORPLA20 composition

Table 2.9. Oxide Composition of AN-105 Simulant and ORPLA20 Glass Composition Used in Melter Tests (wt%).

Component	AN-105 waste contribution	Glass former additives	ORPLA20 (for AN-105)
Loading	31.4%	68.4%	-
Al ₂ O ₃	5.55	1.10	6.65
B ₂ O ₃	0.02	8.72	8.74
CaO	-	3.32	3.32
Cr ₂ O ₃	0.02	0.48	0.50
Fe ₂ O ₃	-	0.19	0.19
K ₂ O	0.53	-	0.53
MgO	-	0.93	0.92
Na ₂ O ^(a)	23.25 + 0.55 ⁽¹⁾ + 0.20 ⁽²⁾	-	24.00
SiO ₂	0.03	42.3	42.33
SnO ₂	-	2.74	2.74
ZnO	-	2.74	2.74
ZrO ₂	-	5.96	5.96
Cl	0.67	-	0.67
F	0.000	-	0.00
P ₂ O ₅	0.000	-	0.00
SO ₃ ^(b)	0.70 ⁽¹⁾	-	0.70
SUM	31.5	68.5	100.0

(a) Simulant was ordered at a concentration of 23.41 wt% Na₂O and modified before each melter test with (1) Na₂SO₄ and (2) NaOH additions to obtain 24 wt% Na₂O in the glass.

(b) Concentration of SO₃ was increased in steps during the melter tests from 0.1 wt% SO₃ in the glass up to 0.7 wt%.

– Empty data field

Table 2.10a. Glass Former Additives for 1 Liter of AN-105 Simulant (8 M Na) and Corresponding Melter Feed Properties.

Additives Source	Feed ORPLA20
Additives in Glass (wt%)	68.6
Kyanite (Al_2SiO_5) 325 Mesh (Kyanite Mining) (g)	18.51
H_3BO_3 (US Borax – Technical Granular) (g)	160.46
Wollastonite NYAD 325 Mesh (NYCO Minerals) (g)	72.57
Cr_2O_3 oxide	5.06 ⁽¹⁾
Olivine (Mg_2SiO_4) 325 Mesh (#180 Unimin) (g)	20.13
SiO_2 (Sil-co-Sil 75 US Silica) (g)	354.47
SnO_2 - Stannous Oxide - Mason color ⁽²⁾	28.57
ZnO (KADOX – 920 Zinc Corp. of America) (g)	28.37
Zircon ZrSiO_4 (Flour) Mesh 325 (AM. Mineral) (g)	92.64
Na_2SO_4	Variable – Table 2.10b
Addition of Sucrose as Reductant (g)	78.5
Simulant Weight for 1 liter (g)	1359
Sum of Additives (g)	962
Sum of Complete Batch (g)	2218
Target Final Volume (l)	1.38
Estimated Density (g/ml)	1.61
Target Glass Produced (g)	1033
Target Weight % Additives in Slurry	39
Target Glass Yield (g/kg of Feed)	466
Target Glass Yield (g/l of Feed)	750
Target Total Solids (g/l of Feed)	969
Target Additives (g/l of Feed)	624

⁽¹⁾ Note that a Cr_2O_3 addition was cut down by 50% to account for K3-brick contribution.

⁽²⁾ Note that SnO_2 from Mason Color was complemented by Alfa product which included iodine as an impurity

Table 2.10b. NaOH and Na_2SO_4 Additions Required to Obtain 24 wt% Na_2O and Various SO_3 Concentrations in the ORPLA20 Glass.

Final SO_3 (wt%)	NaOH needed per kg of feed (grams)	Na_2SO_4 needed per kg of feed (grams)
0.2	7.13	1.69
0.3	6.19	2.53
0.4	5.25	3.37
0.5	4.31	4.22
0.6	3.38	5.06
0.7	2.44	5.90
0.8	1.50	6.75
0.9	0.56	7.59

Table 2.11. LAW Sub-Envelope C2 (AN-102) Simulant Recipe at 8 Molar Sodium.

Envelope Constituents	Simulant AN-102 Including Pretreatment		Glass Oxides	AN-102 Simulant as Oxides (wt%)	Source in Simulant	Order for Addition	Formula Weight	Assay*	Target Weight (g)
-	mg/L	Molarity	Loading	-	In 430 ml water add following compounds in the order listed below				
Al	9922	0.368	Al ₂ O ₃	6.44	Al(NO ₃) ₃ ·9H ₂ O, 60% sol.	1	375.14	0.61	227.31
B	30	0.003	B ₂ O ₃	0.03	H ₃ BO ₃	5	61.83	0.99	0.17
Ca	396	0.010	CaO	0.19	Ca(NO ₃) ₂ ·4H ₂ O	2	236.16	0.99	2.33
Cr	174	0.003	Cr ₂ O ₃	0.09	Na ₂ CrO ₄ ·4H ₂ O	8	234.04	0.99	0.79
K	1604	0.041	K ₂ O	0.66	KOH	7	56.10	0.91	2.53
Na	183920	8.000	Na ₂ O	85.22	NaOH, 50% sol. D=1.53	6	40.00	0.50	160.33
Ni	337	0.006	NiO	0.15	Ni(NO ₃) ₂ ·6H ₂ O	4	290.81	1.00	1.70
Pb	150	0.001	PbO	0.06	PbO	9	223.20	1.00	0.16
Si	73	0.003	SiO ₂	0.05	SiO ₂	10	60.09	0.99	0.16
Cl	3904	0.110	Cl	1.34	NaCl	11	58.45	0.99	6.50
F	2025	0.107	F	0.70	NaF	12	42.00	0.99	4.52
PO ₄	4508	0.047	P ₂ O ₅	1.16	Na ₃ PO ₄ ·12H ₂ O	13	380.12	0.99	17.94
SO ₄ (Nominal) ^{\$}	13648	0.142	SO ₃	3.91	Na ₂ SO ₄	14	142.06	0.99	20.39 ^{\$}
NO ₂	169129	1.503	NO ₂	-	NaNO ₂	20	69.00	1.00	104.21
NO ₃	178997	2.887	NO ₃	-	NaNO ₃	21	84.99	0.99	149.84
CO ₃	44356	0.739	CO ₃	-	Na ₂ CO ₃	22	105.99	1.00	78.34
NH ₃	123	0.007	NH ₃	-	NH ₄ NO ₃	19	80.04	1.00	0.58
Org. Carbon	23569	1.964	-	-	-	-	-	-	-
Formate	26113	0.580	-	-	Sodium Formate (C1)	15	68.01	0.99	39.85
Oxalate	1501	0.017	-	-	Sodium Oxalate (C2)	16	134.00	0.99	2.31
Glycolate	34273	0.451	-	-	Glycolic Acid (C2)	17	76.05	0.71	48.34
Citric Acid	14362	0.075	-	-	Citric Acid (C6)	18	192.12	0.99	14.51
-	-	-	SUM	100.000	Total Simulant Weight				1312.83

- Empty data field.

* Assay refers to the purity of the raw material as specified by the vendor.

^{\$}SO₃ content varied during each run, as given in Table 2.20b. The value given here corresponds to the nominal.

Table 2.12. Target and Analyzed Compositions (wt%) of Six ORPLD Crucible Glasses.

GLASS	ORPLD4		ORPLD5		ORPLD6		ORPLD7		ORPLD8		ORPLD9	
Oxides	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*
Al ₂ O ₃	10.18	9.92	10.18	9.87	10.12	9.81	10.08	9.86	10.03	9.84	8.57	8.41
B ₂ O ₃	12.07	12.86	10.03	10.62	9.87	10.32	9.87	10.10	9.50	10.05	9.50	10.10
CaO	8.03	8.14	8.03	8.11	7.91	8.08	7.91	8.01	7.35	7.71	7.35	7.22
Cr ₂ O ₃	0.50	0.69	0.50	0.69	0.50	0.70	0.50	0.70	0.50	0.65	0.50	0.60
Fe ₂ O ₃	0.30	0.37	0.30	0.36	0.30	0.35	0.30	0.35	0.29	0.32	0.29	0.29
K ₂ O	0.16	0.17	0.16	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.17
MgO	1.00	0.89	1.00	0.92	0.99	0.85	0.99	0.88	0.97	0.85	0.97	0.99
Na ₂ O	21.00	20.30	21.00	20.65	22.00	21.48	22.00	21.49	23.00	22.04	23.00	23.71
NiO	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04
PbO	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.03	0.02	0.02
SiO ₂	37.92	38.38	37.92	37.77	37.33	37.34	37.33	37.45	36.74	37.06	36.74	36.69
SnO ₂	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.18	1.00	1.12	1.00	1.14
V ₂ O ₅	1.00	1.24	2.00	2.49	1.97	2.50	1.00	1.29	1.46	1.59	2.92	2.96
ZnO	3.01	3.17	3.01	3.21	2.97	3.22	2.97	3.16	2.99	3.07	2.99	2.82
ZrO ₂	3.01	3.00	4.05	4.04	3.99	3.91	3.99	3.81	4.02	3.88	4.02	3.60
Cl	0.33	0.33	0.33	0.31	0.35	0.32	0.35	0.32	0.36	0.36	0.36	0.35
F	0.17	NA	0.17	NA	0.18	NA	0.18	NA	0.19	NA	0.19	NA
P ₂ O ₅	0.29	0.31	0.29	0.31	0.30	0.32	0.30	0.35	0.31	0.36	0.31	0.33
SO ₃	0.96	0.85	0.96	0.83	1.01	0.82	1.01	0.87	1.06	1.21	1.06	0.99
SUM	100.0	100.8	100.0	100.6	100.0	100.4	100.0	100.2	100.0	100.5	100.0	100.6

* – Analyzed by X-ray fluorescence except for boron which was measured by DCP

NA – Not analyzed (SUM includes target fluorine value)

Table 2.13. Descriptions of Six As-Melted and Heat Treated ORPLD Crucible Glasses.

Glass ID	As-melted glass	Glass remelted at 1200°C for 1 hour, heat treated for 20 hours at 950°C, and quenched.
ORPLD4	Mostly clear glass. ~ 0.1 vol% of small Cr+Zn crystals	Clear glass
ORPLD5	Mostly clear glass. ~ 0.1 vol% of small Cr+Zn crystals	Mostly clear glass ~0.3 vol% Large sodalite (Na,Ca,Al silicate with S &Cr)
ORPLD6	Mostly clear glass. < 0.1 vol% of small Cr+Zn crystals	Mostly clear glass ~0.3 vol% Large sodalite (Na,Ca,Al silicate with S &Cr)
ORPLD7	Mostly clear glass. < 0.1 vol% of small Cr+Zn crystals	Mostly clear glass ~0.2 vol% Large sodalite (Na,Ca,Al silicate with S &Cr)
ORPLD8	Mostly clear glass. < 0.1 vol% of small Cr+Zn crystals	Mostly clear glass ~0.3 vol% Large sodalite (Na,Ca,Al silicate with S &Cr)
ORPLD9	Mostly clear glass. < 0.1 vol% of small Cr+Zn crystals	Clear glass + submicron Au-Pt crystals

Table 2.14. Measured Sulfate Solubility Limits in Six ORPLD Crucible Glasses.

Sample ID	SO ₃ Content (wt%)	
	Batch Saturation	
	As-Melted	After Acid Wash
ORPLD4S4	1.08	0.94
ORPLD5S4	1.03	0.86
ORPLD6S4	1.11	0.89
ORPLD7S4	1.07	0.87
ORPLD8S4	1.13	0.88
ORPLD9S4	1.14	0.95

Table 2.15. Results of 7-day PCT (at 90°C) and VHT (at 200°C for 24 Days) for Six ORPLD Crucible Glasses.

Glass ID	ORPLD4	ORPLD5	ORPLD6	ORPLD7	ORPLD8	ORPLD9
7-Day PCT, Stainless Steel Vessel; S/V=2000m⁻¹ (ppm)						
B	43.46	31.38	34.64	35.36	40.64	44.62
Na	205.90	195.90	219.60	228.70	268.80	287.10
Si	56.04	56.39	63.40	63.13	69.30	76.22
Normalized Concentrations (g/L)						
B	1.16	1.01	1.13	1.15	1.38	1.51
Na	1.32	1.26	1.35	1.40	1.58	1.68
Si	0.32	0.32	0.36	0.36	0.40	0.44
pH	11.46	11.58	11.67	11.71	11.77	11.78
7-Day PCT Normalized Mass Loss (g/m²)						
B	0.58	0.50	0.56	0.58	0.69	0.76
Na	0.66	0.63	0.67	0.70	0.79	0.84
Si	0.16	0.16	0.18	0.18	0.20	0.22
7-Day PCT Normalized Loss Rate (g/m²/d)						
B	0.08	0.07	0.08	0.08	0.10	0.11
Na	0.09	0.09	0.10	0.10	0.11	0.12
Si	0.02	0.02	0.03	0.03	0.03	0.03
VHT Alteration (24 days at 200°C)						
Alteration Depth (μm)	122	131	164	134	116	377
Alteration Rate (g/m ² /day)*	13	14	18	15	13	42

* Alteration rates calculated using estimated density of 2.65 g/cc

Table 2.16. Viscosities and Electrical Conductivities of Six ORPLD Crucible Glasses.

Glass ID	ORPLD4	ORPLD5	ORPLD6	ORPLD7	ORPLD8	ORPLD9
Viscosity (poise)						
900°C	662	952	691	881	794	549
950°C	282	393	302	366	330	242
1000°C	138	187	149	172	156	119
1050°C	75	99	81	90	82	65
1100°C	44	57	48	51	47	38
1150°C	28	36	30	31	29	23
1200°C	19	23	20	20	19	15
1250°C	13	16	14	13	13	10
Electrical Conductivity (S/cm)						
900°C	0.155	0.164	0.189	0.171	0.191	0.188
950°C	0.196	0.207	0.232	0.209	0.240	0.248
1000°C	0.242	0.255	0.280	0.252	0.295	0.314
1050°C	0.295	0.310	0.334	0.300	0.354	0.386
1100°C	0.354	0.371	0.392	0.351	0.418	0.462
1150°C	0.420	0.439	0.456	0.407	0.487	0.542
1200°C	0.493	0.514	0.524	0.466	0.559	0.625
1250°C	0.571	0.595	0.597	0.530	0.635	0.710

Table 2.17. Results of K-3 Corrosion Testing for Four ORPLD Crucible Glasses.

Glass ID	Neck loss (inches)	Depth of altered zone (inches)	Half-down loss (inches)
ORPLD6	0.040	0.028	Coupon expanded – no measurable loss
ORPLD7	0.047	0.026	Coupon expanded – no measurable loss
ORPLD8	0.066	0.028	0.001
ORPLD9	0.063	0.028	0.001

Table 2.18. Summary of Test Results for Selected ORPLD Glass Formulation ORPLD6 and Comparison to ILAW Requirements.

Test	Requirement [53, 54]	Test Result for ORPLD6
Density of glass	< 3.7 g/cc	2.57 g/cc
Crystalline Phase	Phase identification	Clear homogeneous glass with not more than 0.2 vol% crystals on average after heat treatment at 950°C for 20 hours
Liquidus	< 950°C	< 950°C
Centerline Canister Cooling	Phase identification	Not measured
PCT B (g/m ²)	< 2.0 g/m ²	0.56 g/m ²
PCT Na (g/m ²)	< 2.0 g/m ²	0.67 g/m ²
PCT Si (g/m ²)	< 2.0 g/m ²	0.18 g/m ²
VHT at 200°C (g/m ² /day)	< 50 g/m ² /day	18 g/m ² /day
Viscosity (poise) at 1100°C	10 to 150 P	48 P
Conductivity (S/cm) at 1100°C	0.2 to 0.7 S/cm	0.392 S/cm
T _G (°C)	Report for modeling	Not measured

*Density measured for melter glass 10A-G-53C of the ORPLD6 composition

Table 2.19. Oxide Composition of AN-102 Simulant and ORPLD6 Glass Composition Used in Melter Tests (wt%).

Component	AN-102 waste contribution	Glass former additives	ORPLD6 (for AN-102)
Loading	25.89%	74.11%	-
Al ₂ O ₃	1.55	8.56	10.09
B ₂ O ₃	0.01	9.85	9.85
CaO	0.05	7.86	7.89
Cr ₂ O ₃	0.02	0.48	0.50
Fe ₂ O ₃	-	0.28	0.28
K ₂ O	0.17	-	0.17
MgO	-	1.00	1.00
Na ₂ O ^(a)	20.44 + 0.93 ⁽¹⁾ + 0.63 ⁽²⁾	-	22.00
NiO	0.04	-	0.04
PbO	0.01	-	0.01
SiO ₂	0.01	37.26	37.24
V ₂ O ₅	-	1.96	1.96
ZnO	-	2.96	2.96
ZrO ₂	-	3.99	3.98
Cl	0.35	-	0.35
F	0.18	-	0.18
P ₂ O ₅	0.30	-	0.30
SO ₃ ^(b)	1.20 ⁽¹⁾	-	1.20
SUM	25.9	74.1	100.0

(a) Simulant was ordered at a concentration of 19.37 wt% Na₂O and modified before each melter test with (1) Na₂SO₄ and (2) NaOH additions to obtain 21.0 wt% Na₂O in the glass.

(b) Concentration of SO₃ was increased in steps during the melter tests from 0.7 wt% SO₃ in the glass up to 1.3 wt%.

– Empty data field

Table 2.20a. Glass Former Additives for 1 Liter of AN-102 Simulant (8 M Na) and Corresponding Melter Feed Properties.

Additives Source	Feed ORPLD6
Additives in Glass (wt%)	74.1
Kyanite (Al_2SiO_5) 325 Mesh (Kyanite Mining) (g)	166.51
H_3BO_3 (US Borax – Technical Granular) (g)	197.69
Wollastonite NYAD 325 Mesh (NYCO Minerals) (g)	187.03
Cr_2O_3 oxide	5.49
Fe_2O_3 (Prince Manufacturing) (g)	0
Olivine (Mg_2SiO_4) 325 Mesh (#180 Unimin) (g)	20.49
SiO_2 (Sil-co-Sil 75 US Silica) (g)	223.78
V_2O_5 – Pulva Ground - Stratcor	22.15
ZnO (KADOX – 920 Zinc Corp. of America) (g)	33.47
Zircon ZrSiO_4 (Flour) Mesh 325 (AM. Mineral) (g)	67.55
Na_2SO_4	Variable – Table 2.20b
Addition of Sucrose as Reductant (g)	37.86
Simulant Weight for 1 liter (g)	1313
Sum of Additives (g)	962
Sum of Complete Batch (g)	2275
Target Final Volume (l)	1.34
Estimated Density (g/ml)	1.70
Target Glass Produced (g)	1127
Target Weight % Additives in Slurry	42
Target Glass Yield (g/kg of Feed)	495
Target Glass Yield (g/l of Feed)	842
Target Total Solids (g/l of Feed)	1068
Target Additives (g/l of Feed)	719

Table 2.20b. NaOH and Na_2SO_4 Additions Required to Obtain 22 wt% Na_2O and Various SO_3 Concentrations in the ORPLD6 Glass.

Final SO_3 (wt%)	NaOH needed per kg of feed (grams)	Na_2SO_4 needed per kg of feed (grams)
0.0	20.20	-
0.7	13.16	6.33
0.8	12.16	7.23
0.9	11.15	8.14
1.0	10.15	9.04
1.1	9.14	9.95
1.2	8.14	10.85
1.3	7.13	11.76

Table 2.21. LAW Sub-Envelope B2 (AZ-102) Waste Simulant Recipe at 5.5 Molar Sodium.

Envelope Constituents	Simulant AZ-102 Including Pretreatment		Glass Oxides	AZ-102 Simulant as Oxides (wt%)	Source in Simulant	Order for Addition	Formula Weight	Assay	Target Weight (g)
-	mg/L	Molarity	Loading	-	In 714 ml water add following compounds in the order listed.				
Al	339	0.013	Al ₂ O ₃	0.30	Al(NO ₃) ₃ ·9H ₂ O, 60% sol.	2	375.14	0.61	7.76
Cr	1289	0.025	Cr ₂ O ₃	0.90	Na ₂ CrO ₄ ·4H ₂ O	5	234.04	0.99	5.89
K	5841	0.149	K ₂ O	3.34	KOH	4	56.098	0.91	9.23
Na	126445	5.500	Na ₂ O	80.96	NaOH, 50% sol. d=1.53	3	40.00	0.50	348.45
Si	472	0.017	SiO ₂	0.48	SiO ₂	8	60.09	0.99	1.02
Cl	157	0.004	Cl	0.07	NaCl	10	58.45	0.99	0.26
F	1171	0.062	F	0.56	NaF	11	42.00	0.99	2.62
PO ₄	679	0.007	P ₂ O ₅	0.24	Na ₃ PO ₄ ·12H ₂ O	9	380.12	0.99	2.75
SO ₄ (Nominal) ^{\$}	32952	0.343	SO ₃	13.04	Na ₂ SO ₄	14	142.06	0.99	49.22 ^{\$}
NO ₂	0	0	NO ₂	-	[#] NaNO ₂	14	69.00	1.00	0
NO ₃	21551	0.348	NO ₃	-	NaNO ₃	15	84.99	0.99	26.61
CO ₃	0	0	CO ₃	-	[#] Na ₂ CO ₃	1	105.99	1.00	0
Org.Carbon	1671	0.139	-	-	-	-	-	-	-
Oxalate	6164	0.070	-	-	Oxalic Acid (C2)	13	126.00	1.00	8.83
-	-	-	SUM	100.00	Total Simulant Weight				1176.63

- Empty data field.

* Assay refers to the purity of the raw material as specified by the vendor.

[#] Na₂CO₃ and NaNO₂ were omitted to accommodate sulfate addition as Na₂SO₄ without excessive decrease in the amount of added NaOH

^{\$} SO₃ content varied during each run, as given in Table 2.30b. The value given here corresponds to the nominal.

Table 2.22. Target and Analyzed Compositions (wt%) of Fourteen ORPLF Crucible Glasses.

GLASS	ORPLF1		ORPLF2		ORPLF3		ORPLF4		ORPLF5		ORPLF6		ORPLF7	
Oxides	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*
Al ₂ O ₃	10.03	9.87	9.89	9.59	9.76	9.54	8.60	8.61	9.62	9.45	8.48	8.29	8.60	8.33
B ₂ O ₃	9.75	10.18	9.61	10.00	9.48	9.54	9.50	9.49	9.34	8.46	9.36	8.42	9.50	8.95
CaO	10.00	9.81	9.86	9.88	9.72	9.82	9.72	9.69	9.58	9.83	9.58	9.87	9.72	9.87
Cr ₂ O ₃	0.55	0.73	0.55	0.75	0.56	0.76	0.56	0.77	0.56	0.76	0.56	0.79	0.56	0.75
Fe ₂ O ₃	0.31	0.34	0.30	0.35	0.30	0.35	0.30	0.36	0.29	0.36	0.29	0.37	0.30	0.36
K ₂ O	0.41	0.38	0.45	0.43	0.50	0.45	0.50	0.44	0.54	0.49	0.54	0.51	0.50	0.48
Li ₂ O	3.75	4.10	3.70	4.07	3.65	4.03	3.50	3.82	3.59	3.92	3.45	3.81	4.35	4.75
MgO	1.01	0.94	0.99	0.89	0.98	0.86	0.98	0.83	0.97	0.84	0.97	0.90	0.98	0.92
Na ₂ O	10.00	10.20	11.00	11.03	12.00	11.78	12.00	11.11	13.00	12.69	13.00	11.97	12.00	11.77
SiO ₂	43.35	43.50	42.74	42.79	42.14	42.52	42.14	42.75	41.54	42.05	41.54	42.14	42.14	42.15
SnO ₂	0.88	1.09	0.86	1.13	0.85	1.13	0.85	1.14	0.84	0.99	0.84	0.99	0.00	0.00
V ₂ O ₅	1.25	1.55	1.24	1.52	1.22	1.53	2.50	3.07	1.20	1.50	2.47	3.11	2.50	3.10
ZnO	3.00	3.10	2.96	3.10	2.91	3.12	2.91	3.09	2.87	3.08	2.87	3.13	2.91	3.11
ZrO ₂	4.00	3.84	3.94	3.87	3.88	3.86	3.88	3.81	3.83	3.69	3.83	3.72	3.88	3.78
Cl	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.02	0.01	0.03	0.01	0.01
F	0.07	NA	0.08	NA	0.08	NA	0.08	NA	0.09	NA	0.09	NA	0.08	NA
P ₂ O ₅	0.03	0.04	0.03	0.04	0.04	0.05	0.04	0.05	0.04	0.05	0.04	0.05	0.04	0.05
SO ₃	1.61	0.92	1.77	1.15	1.93	0.93	1.93	1.10	2.09	1.08	2.09	1.13	1.93	1.32
SUM	100.0	100.7	100.0	100.7	100.0	100.4	100.0	100.2	100.0	99.4	100.0	99.3	100.0	99.8

* – Analyzed by X-ray fluorescence except for boron and lithium which were measured by DCP

NA – Not analyzed

Table 2.22. Target and Analyzed Compositions (wt%) of Fourteen ORPLF Crucible Glasses (continued).

GLASS	ORPLF8		ORPLF9		ORPLF10		ORPLF11		ORPLF12		ORPLF13		ORPLF14	
Oxides	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*
Al ₂ O ₃	8.60	8.28	7.60	7.32	8.60	8.29	8.60	8.33	8.60	8.10	8.60	7.97	8.60	8.13
B ₂ O ₃	8.85	8.66	8.85	8.52	9.50	8.85	9.50	9.02	9.50	9.05	9.50	9.20	9.50	9.07
CaO	9.72	9.98	9.72	9.78	10.57	10.66	9.72	9.80	9.72	10.21	10.57	11.54	10.57	11.07
Cr ₂ O ₃	0.56	0.79	0.56	0.78	0.56	0.75	0.56	0.76	0.56	0.71	0.56	0.75	0.56	0.73
Fe ₂ O ₃	0.30	0.36	0.30	0.36	0.30	0.35	0.30	0.36	0.30	0.33	0.00	0.00	0.00	0.00
K ₂ O	0.50	0.50	0.50	0.48	0.50	0.47	0.50	0.47	0.50	0.51	0.50	0.52	0.50	0.53
Li ₂ O	5.00	5.16	3.50	3.78	3.50	3.81	3.50	3.77	3.50	3.73	3.50	3.77	3.71	3.89
MgO	0.98	0.85	0.98	0.88	0.98	0.87	0.98	0.90	0.98	0.86	0.00	0.00	0.00	0.00
Na ₂ O	12.00	11.44	12.00	11.87	12.00	11.88	12.00	11.45	12.00	12.49	12.00	11.28	12.00	11.93
SiO ₂	42.14	42.18	41.82	41.42	42.14	42.54	42.14	42.47	42.14	41.39	42.14	41.27	42.14	41.36
SnO ₂	0.00	0.01	0.85	1.04	0.00	0.01	0.60	0.80	0.00	0.01	1.00	1.19	1.00	1.23
V ₂ O ₅	2.50	3.12	2.50	3.10	2.50	3.02	2.75	3.39	2.75	2.99	2.72	3.18	2.50	2.80
ZnO	2.91	3.15	2.91	3.12	2.91	3.02	2.91	3.08	2.91	2.91	2.91	3.15	2.91	2.97
ZrO ₂	3.88	3.82	3.88	3.78	3.88	3.73	3.88	3.79	4.49	4.17	3.95	3.92	3.95	3.82
Cl	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01
F	0.08	NA	0.08	NA	0.08	NA	0.09	NA	0.09	NA	0.08	NA	0.08	NA
P ₂ O ₅	0.04	0.05	2.00	2.10	0.04	0.04	0.04	0.08	0.04	0.05	0.04	0.05	0.04	0.05
SO ₃	1.93	1.47	1.93	1.43	1.93	1.24	1.93	1.16	1.93	2.10	1.93	1.97	1.93	1.96
SUM	100.0	99.9	100.0	99.8	100.0	99.6	100.0	99.7	100.0	99.7	100.0	99.9	100.0	99.6

* – Analyzed by X-ray fluorescence except for boron and lithium which was measured by DCP

NA – Not analyzed

Table 2.23. Descriptions of Fourteen As-Melted and Heat Treated ORPLF Crucible Glasses.

Glass ID	As-melted glass	Glass remelted at 1200°C for 1 hour, heat treated for 20 hours at 950°C, and quenched.
ORPLF1	Mostly clear glass. ~0.2 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.2 vol% Cr oxide crystals + Zn and Sn
ORPLF2	Mostly clear glass. ~0.1 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.2 vol% Cr oxide crystals + Zn and Sn
ORPLF3	Mostly clear glass. ~0.2 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.3 vol% Cr oxide crystals + Zn and Sn
ORPLF4	Mostly clear glass. ~0.1 vol% tiny Cr oxide crystals	Mostly clear glass. <0.1 vol% Cr oxide crystals + Zn and Sn
ORPLF5	Mostly clear glass. 0.1-0.2 vol% Cr-Zn oxide crystals	Clear glass. <<0.1 vol% Cr-Zn oxide crystals
ORPLF6	Mostly clear glass. 0.1-0.2 vol% Cr-Zn oxide crystals	Clear glass. <<0.1 vol% Cr-Zn oxide crystals
ORPLF7	Mostly clear glass. ~0.2 vol% Cr-Zn oxide crystals	Mostly clear glass. ~0.1 vol% Cr-Zn oxide crystals
ORPLF8	Mostly clear glass. ~0.2 vol% Cr-Zn oxide crystals	Mostly clear glass. <0.1 vol% Cr-Zn oxide crystals
ORPLF9	Clear glass. <<0.1 vol% Cr-Zn oxide crystals	Mostly clear glass. <0.1 vol% Cr-Zn oxide crystals
ORPLF10	Mostly clear glass. ~0.3 vol% Cr-Zn oxide crystals	~0.1-0.2 vol% Cr-Zn oxide crystals
ORPLF11	Mostly clear glass. ~0.1 vol% Cr-Zn oxide crystals	Clear glass. <<0.1% Cr-Zn oxide crystals
ORPLF12	Mostly clear glass. ~0.2 vol% Cr-Zn oxide crystals	~0.1-0.2 vol.% Cr-Zn oxide crystals
ORPLF13	Clear glass. <<0.1 vol% Cr-Zn oxide crystals	Clear glass. Few platinum particles and Cr-Zn crystals
ORPLF14	Clear glass. <<0.1 vol% Cr-Zn oxide crystals	Mostly clear glass. <0.1 vol% Cr-Zn oxide crystals

Table 2.24. Measured Sulfate Solubilities in Twelve ORPLF Crucible Glasses.

Sample ID	SO ₃ Content (wt%)	
	Batch Saturation	
	As-Melted	After Acid Wash
ORPLF1S4	1.39	1.26
ORPLF2S4	1.42	1.23
ORPLF3S4	1.64	1.24
ORPLF4S4	1.73	1.32
ORPLF5S4	1.49	1.19
ORPLF6S4	1.77	1.28
ORPLF7S4	1.86	1.44
ORPLF8S4	1.85	1.45
ORPLF9S4	1.66	1.40
ORPLF10S4	1.79	1.41
ORPLF11S4	1.71	1.35
ORPLF12S4	1.70	1.33
ORPLF13S4	1.61	1.36
ORPLF14S4	1.61	1.41

Table 2.25. Results of 7-day PCT (at 90°C) and VHT (at 200°C for 24 Days) for Fourteen ORPLF Crucible Glasses.

Glass ID	ORPLF1	ORPLF2	ORPLF3	ORPLF4	ORPLF5	ORPLF6	ORPLF7	ORPLF8	ORPLF9	ORPLF10	ORPLF11	ORPLF12	ORPLF13	ORPLF14
7-Day PCT, Stainless Steel Vessel; S/V=2000m⁻¹ (ppm)														
B	4.71	4.81	8.33	8.96	9.15	9.53	9.78	10.21	17.04	10.52	9.60	10.40	5.98	7.66
Li	7.40	9.13	9.41	7.61	13.13	10.03	12.75	15.36	12.76	11.32	9.15	9.61	7.85	9.30
Na	38.53	53.33	54.73	43.47	114.60	66.50	63.48	57.61	65.59	81.49	51.49	54.77	44.61	49.37
Si	22.64	24.56	27.02	31.58	24.22	29.38	32.28	40.77	50.31	30.13	33.48	35.28	29.10	35.27
Normalized Concentrations (g/L)														
B	0.16	0.16	0.28	0.30	0.32	0.33	0.33	0.37	0.62	0.36	0.33	0.35	0.20	0.26
Li	0.42	0.53	0.56	0.47	0.79	0.63	0.63	0.66	0.78	0.70	0.56	0.59	0.48	0.54
Na	0.52	0.65	0.61	0.49	1.19	0.69	0.71	0.65	0.74	0.92	0.58	0.62	0.50	0.55
Si	0.11	0.12	0.14	0.16	0.12	0.15	0.16	0.21	0.26	0.15	0.17	0.18	0.15	0.18
pH	10.75	10.85	10.91	10.99	10.88	10.98	11.09	11.28	10.98	10.89	10.98	10.99	11.02	11.05
7-Day PCT Normalized Mass Loss (g/m²)														
B	0.08	0.08	0.14	0.15	0.16	0.16	0.17	0.19	0.31	0.18	0.16	0.18	0.10	0.13
Li	0.21	0.27	0.28	0.23	0.39	0.31	0.32	0.33	0.39	0.35	0.28	0.30	0.24	0.27
Na	0.26	0.33	0.31	0.24	0.59	0.34	0.36	0.32	0.37	0.46	0.29	0.31	0.25	0.28
Si	0.06	0.06	0.07	0.08	0.06	0.08	0.08	0.10	0.13	0.08	0.08	0.09	0.07	0.09
7-Day PCT Normalized Loss Rate (g/m²/d)														
B	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.03	0.02	0.03	0.01	0.02
Li	0.03	0.04	0.04	0.03	0.06	0.04	0.05	0.05	0.06	0.05	0.04	0.04	0.03	0.04
Na	0.04	0.05	0.04	0.03	0.08	0.05	0.05	0.05	0.05	0.07	0.04	0.04	0.04	0.04
Si	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
VHT Alteration (24 days at 200°C)														
Alteration Depth (μm)	43	168	131	193	75 to 200	151	164	95	273	122	236	222	108	94
Alteration Rate (g/m ² /day)*	5	19	14	21	8 to 22	17	18	10	30	13	26	25	12	10

* Alteration rates calculated using estimated density of 2.65 g/cc

Table 2.26. Viscosities and Electrical Conductivities of Eleven ORPLF Crucible Glasses.

Glass ID	ORPLF1	ORPLF2	ORPLF3	ORPLF4	ORPLF7	ORPLF8	ORPLF9	ORPLF10	ORPLF12	ORPLF13	ORPLF14
Viscosity (poise)											
900°C	1076	833	776	660	401	301	743	537	601	637	647
950°C	435	362	339	287	177	145	302	240	269	270	268
1000°C	206	177	166	141	90	77	144	120	134	132	129
1050°C	109	95	90	76	51	44	77	66	73	71	70
1100°C	64	55	52	44	32	27	45	39	43	42	41
1150°C	40	34	33	27	21	18	29	24	27	26	26
1200°C	27	22	21	18	14	12	19	16	18	18	18
1250°C	19	15	15	12	10	9	14	11	12	12	13
Electrical Conductivity (S/cm)											
900°C	0.062	0.074	0.074	0.082	0.106	0.135	0.093	0.091	0.089	0.085	0.112
950°C	0.086	0.100	0.100	0.111	0.157	0.178	0.126	0.121	0.122	0.120	0.153
1000°C	0.115	0.131	0.131	0.146	0.216	0.229	0.167	0.158	0.161	0.162	0.199
1050°C	0.152	0.170	0.170	0.189	0.280	0.290	0.215	0.202	0.210	0.210	0.251
1100°C	0.196	0.216	0.216	0.239	0.349	0.361	0.273	0.254	0.267	0.264	0.308
1150°C	0.249	0.269	0.269	0.299	0.420	0.442	0.341	0.314	0.335	0.324	0.369
1200°C	0.311	0.330	0.330	0.367	0.492	0.534	0.419	0.382	0.414	0.388	0.432
1250°C	0.382	0.401	0.401	0.445	0.565	0.637	0.508	0.459	0.504	0.456	0.499

Table 2.27. Results of K-3 Corrosion Testing for Ten ORPLF Crucible Glasses.

Glass ID	Neck loss (inches)	Depth of altered zone (inches)	Half-down loss (inches)
ORPLF4	0.009	0.030	0
ORPLF4-Repeat	0.003 Al ₂ O ₃ contamination	0.025	Coupon expanded – no measurable loss
ORPLF7	0.010	0.029	0.003
ORPLF7-Repeat	0.020	0.030	0.002
ORPLF8	0.018	0.031	Coupon expanded – no measurable loss
ORPLF9	0.004	0.025	0
ORPLF10	0.009	0.029	0
ORPLF10-Repeat	0.005	0.027	Coupon expanded – no measurable loss
ORPLF13	0.013	0.030	0.0005
ORPLF14	0.017	0.030	Coupon expanded – no measurable loss

Table 2.28. Summary of Test Results for Selected ORPLF Glass Formulation ORPLF7 and Comparison to ILAW Requirements.

Test	Requirement [53, 54]	Test Result for ORPLF7
Density of glass	< 3.7 g/cc	2.62 g/cc
Crystalline Phase	Phase identification	Clear homogeneous glass with less than 0.1 vol% crystals after heat treatment at 850°C for 20 hours
Liquidus	< 950°C	< 950°C
Centerline Canister Cooling	Phase identification	Not measured
PCT B (g/m ²)	< 2.0 g/m ²	0.17 g/m ²
PCT Li (g/m ²)	< 2.0 g/m ²	0.32 g/m ²
PCT Na (g/m ²)	< 2.0 g/m ²	0.36 g/m ²
PCT Si (g/m ²)	< 2.0 g/m ²	0.08 g/m ²
VHT at 200°C (g/m ² /day)	< 50 g/m ² /day	18 g/m ² /day
Viscosity (poise) at 1100°C	10 to 150 P	32 P
Conductivity (S/cm) at 1100°C	0.2 to 0.7 S/cm	0.349 S/cm
T _G (°C)	Report for modeling	Not measured

*Density measured for melter glass Z10-G-153B of the ORPLF7 composition

Table 2.29. Oxide Composition of AZ-102 Simulant and ORPLF7 Glass Composition Used in Melter Tests (wt%).

Component	AZ-102 waste contribution	Glass former additives	ORPLF7 (for AZ-102)
Loading	14.3%	85.7%	-
Al ₂ O ₃	0.04	8.61	8.65
B ₂ O ₃	-	9.54	9.54
CaO	-	9.78	9.78
Cr ₂ O ₃	0.12	0.44	0.56
Fe ₂ O ₃	-	0.23	0.23
K ₂ O	0.50	-	0.43
Li ₂ O	-	4.37	4.37
MgO	-	0.98	0.98
Na ₂ O ^(a)	10.45 + 1.16 ⁽¹⁾ + 0.39 ⁽²⁾	-	12.00
SiO ₂	0.06	42.44	42.50
V ₂ O ₅	-	2.50	2.50
ZnO	-	2.92	2.92
ZrO ₂	-	3.92	3.92
Cl	0.01	-	0.01
F	0.08	-	0.07
P ₂ O ₅	0.04	-	0.03
SO ₃ ^(b)	1.500 ⁽¹⁾	-	1.50
SUM	14.35	85.65	100.0

(a) Simulant was ordered at a concentration of 10.45 wt% Na₂O and modified before each melter test with (1) Na₂SO₄ and (2) NaOH additions to obtain 12.00 wt% Na₂O in the glass.

(b) Concentration of SO₃ was increased in steps during the melter tests.

– Empty data field

Table 2.30a. Glass Former Additives for 1 Liter of LAW AZ-102 Simulant (5.5 M Na) and Corresponding Melter Feed Properties.

Additives Source	Feed ORPLF7
Additives in Glass (wt%)	85.7
Kyanite (Al_2SiO_5) 325 Mesh (Kyanite Mining) (g)	208.79
H_3BO_3 (US Borax – Technical Granular) (g)	239.27
Wollastonite NYAD 325 Mesh (NYCO Minerals) (g)	303.76
Cr_2O_3 oxide	6.19
Li_2CO_3 (Chemetall Foote Co, Tech Grade)	154.48
Olivine (Mg_2SiO_4) 325 Mesh (#180 Unimin) (g)	24.05
SiO_2 (Sil-co-Sil 75 US Silica) (g)	312.34
V_2O_5 – Pulva Ground - Stratcor	35.53
ZnO (KADOX – 920 Zinc Corp. of America) (g)	41.33
Zircon ZrSiO_4 (Flour) Mesh 325 (AM. Mineral) (g)	83.12
Na_2SO_4	Variable – Table 2.30b
Addition of Sucrose as Reductant (g)	3.46
Simulant Weight for 1 liter (g)	1177
Sum of Additives (g)	1412
Sum of Complete Batch (g)	2589
Target Final Volume (l)	1.53
Estimated Density (g/ml)	1.7
Target Glass Produced (g)	1420
Target Weight % Additives in Slurry	55
Target Glass Yield (g/kg of Feed)	549
Target Glass Yield (g/l of Feed)	922
Target Total Solids (g/l of Feed)	1008
Target Additives (g/l of Feed)	917

*Preliminary feed test was done with a 5M Na-simulant (density of feed = 1.64) but rheology indicated a low yield stress of 2.7 Pa) and a 10% increase in concentration was selected for the melter test. See

Table 2.30b. NaOH and Na_2SO_4 Additions Required to Obtain 12 wt% Na_2O and Various SO_3 Concentrations in the ORPLF7 Glass.

Final SO_3 (wt%)	NaOH needed per kg of feed (grams)	Na_2SO_4 needed per kg of feed (grams)
0.00	22.3	0
1.00	11.15	10.02
1.10	10.03	11.03
1.20	8.92	12.03
1.30	7.80	13.03
1.40	6.69	14.03
1.50	5.57	15.04
1.60	4.46	16.04
1.70	3.34	17.04

Table 2.31. LAW Sub-Envelope A2 (AP-101) Waste Simulant Recipe at 8.45 Molar Sodium.

Envelope Constituents	Simulant AP-101 Including Pretreatment		Glass Oxides	Simulant as Oxides (wt%)	Source in Simulant	Order for Addition	Formula Weight	Assay*	Target Weight (g)
-	mg/L	Molarity	Loading	100%	In 439 ml water ^{\$} add following compounds in the order listed below				
Al	9625	0.357	Al ₂ O ₃	5.26	Al(NO ₃) ₃ ·9H ₂ O, 60% sol.	1	375.14	0.61	220.51
B	12	0.001	B ₂ O ₃	0.01	H ₃ BO ₃	2	61.83	0.99	0.07
Cr	749	0.014	Cr ₂ O ₃	0.32	Na ₂ CrO ₄ ·4H ₂ O	8	234.04	0.99	3.42
K	56301	1.440	K ₂ O	19.61	KOH	7	56.10	0.91	88.97
Na	183920	8.000 ^{\$}	Na ₂ O	71.67	NaOH, 50% sol. d=1.53	6	40.00	0.50	226.00
Ni	82	0.001	NiO	0.03	NiO	3	74.69	1.00	0.10
Pb	95	0.0005	PbO	0.03	PbO	4	223.20	1.00	0.10
Si	157	0.006	SiO ₂	0.10	SiO ₂	5	60.09	0.99	0.34
Cl	2730	0.077	Cl	0.79	NaCl	10	58.45	0.99	4.55
F	1083	0.057	F	0.31	NaF	11	42.00	0.99	2.42
PO ₄	2251	0.024	P ₂ O ₅	0.49	Na ₃ PO ₄ ·12H ₂ O	9	380.12	0.99	9.10
SO ₄ (Nominal) ^{\$}	5764	0.060	SO ₃	1.39	Na ₂ SO ₄	12	142.06	0.99	8.61 ^{\$}
NO ₂	58110	1.263	-	-	NaNO ₂	16	69.00	1.00	87.60
NO ₃	183067	2.953	-	-	NaNO ₃	17	84.99	0.99	161.61
CO ₃	44775	0.746	-	-	Na ₂ CO ₃	18	105.99	1.00	79.08
Org. Carbon	2718	0.227	-	-	-	-	-	-	-
Acetate	3025	0.051	-	-	Sodium Acetate (C2)	13	136.08	0.99	7.04
Formate	2213	0.049	-	-	Sodium Formate (C1)	14	68.01	0.99	3.38
Oxalate	3321	0.038	-	-	Sodium Oxalate (C2)	15	134.00	0.99	5.11
-	-	-	SUM	100.00	Total simulant Weight				1346.99

"-" Empty data field.

Assay refers to the purity of the raw material as specified by the vendor.

^{\$} SO₃ content varied during each run, as given in Table 2.40b. The value given here corresponds to the nominal.

Table 2.32. Target and Analyzed Compositions (wt%) of Twelve ORPLG Crucible Glasses.

GLASS	ORPLG1		ORPLG2		ORPLG3		ORPLG4		ORPLG5		ORPLG6	
Oxides	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*
Al ₂ O ₃	10.04	9.86	9.99	9.63	9.95	9.64	9.95	9.67	9.95	9.63	6.77	6.59
B ₂ O ₃	8.90	9.67	8.82	9.57	8.74	9.32	8.74	9.46	8.74	9.22	8.70	9.46
CaO	2.23	2.20	2.20	2.33	2.18	2.30	2.18	2.29	2.77	2.85	2.75	2.97
Cr ₂ O ₃	0.60	0.70	0.60	0.72	0.60	0.73	0.60	0.73	0.60	0.73	0.60	0.75
Fe ₂ O ₃	0.30	0.31	0.29	0.31	0.29	0.32	0.29	0.31	0.00	0.00	0.29	0.32
K ₂ O	5.06	4.83	5.20	5.13	5.34	5.38	5.34	5.31	5.34	5.28	5.40	5.33
MgO	0.96	0.85	0.96	0.80	0.95	0.83	0.95	0.91	0.00	0.00	0.98	0.81
Na ₂ O	18.50	18.74	19.00	18.81	19.50	18.66	19.50	19.42	19.50	19.23	19.75	19.15
NiO	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
PbO	0.01	0.03	0.01	0.03	0.01	0.02	0.01	0.03	0.01	0.02	0.01	0.03
SiO ₂	41.27	41.73	40.89	40.82	40.50	40.80	40.50	40.88	40.79	40.96	41.75	41.44
SnO ₂	2.97	3.25	2.94	3.42	2.91	3.47	4.80	4.70	2.91	3.23	2.90	3.42
ZnO	2.45	2.34	2.43	2.48	2.40	2.45	2.40	2.40	2.77	2.77	3.48	3.65
ZrO ₂	5.93	5.25	5.88	5.64	5.82	5.55	3.93	3.52	5.82	5.48	5.80	5.71
Cl	0.20	0.21	0.21	0.22	0.21	0.23	0.21	0.23	0.21	0.21	0.22	0.23
F	0.08	NA	0.08	NA	0.08	NA	0.08	NA	0.08	NA	0.09	NA
P ₂ O ₅	0.13	0.14	0.13	0.15	0.13	0.16	0.13	0.16	0.13	0.16	0.14	0.16
SO ₃	0.36	0.33	0.37	0.32	0.38	0.36	0.38	0.38	0.38	0.36	0.38	0.36
SUM	100.0	100.5	100.0	100.5	100.0	100.3	100.0	100.5	100.0	100.2	100.0	100.5

* – Analyzed by X-ray fluorescence except for boron which was measured by DCP
NA – Not analyzed (SUM includes target fluorine value)

Table 2.32. Target and Analyzed Compositions (wt%) of Twelve ORPLG Crucible Glasses (continued).

GLASS	ORPLG7		ORPLG8		ORPLG9		ORPLG10		ORPLG11		ORPLG12	
Oxides	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*	Target	Analyzed*
Al ₂ O ₃	6.77	6.55	6.75	6.54	6.74	6.48	6.72	6.44	6.75	6.43	6.75	6.44
B ₂ O ₃	8.65	8.45	8.57	8.44	8.49	8.39	8.40	8.35	8.57	8.48	8.57	8.42
CaO	2.74	2.94	2.71	2.97	2.69	2.93	2.66	2.89	3.96	4.35	2.71	2.91
Cr ₂ O ₃	0.59	0.74	0.59	0.75	0.59	0.74	0.59	0.74	0.59	0.78	0.59	0.77
Fe ₂ O ₃	0.29	0.32	0.29	0.33	0.28	0.33	0.28	0.32	0.00	0.00	0.29	0.32
K ₂ O	5.47	5.45	5.61	5.75	5.75	5.87	5.88	6.05	5.61	5.74	5.61	5.64
MgO	0.97	0.85	0.96	0.87	0.95	0.82	0.94	0.85	0.00	0.00	0.96	0.86
Na ₂ O	20.00	20.20	20.50	19.96	21.00	20.18	21.50	20.79	20.50	19.45	20.50	20.79
NiO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.03
PbO	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.03	0.01	0.02	0.01	0.02
SiO ₂	41.55	41.27	41.15	41.26	40.75	40.42	40.35	40.31	41.15	40.61	41.15	40.57
SnO ₂	2.88	3.08	2.86	3.01	2.83	3.40	2.80	3.21	2.86	3.49	2.86	3.08
ZnO	3.46	3.52	3.43	3.58	3.39	3.63	3.36	3.50	3.43	3.71	3.43	3.54
ZrO ₂	5.77	5.39	5.71	5.36	5.66	5.60	5.60	5.39	5.71	5.78	3.86	3.61
Cl	0.22	0.22	0.23	0.23	0.23	0.23	0.24	0.23	0.23	0.23	0.23	0.23
F	0.09	NA	0.09	NA	0.09	NA	0.09	NA	0.09	NA	0.09	NA
P ₂ O ₅	0.14	0.16	0.14	0.15	0.14	0.16	0.15	0.17	0.14	0.17	2.00	2.05
SO ₃	0.39	0.35	0.40	0.36	0.41	0.36	0.42	0.40	0.40	0.38	0.40	0.35
SUM	100.0	99.6	100.0	99.7	100.0	99.7	100.0	99.8	100.0	99.7	100.0	99.7

* – Analyzed by X-ray fluorescence except for boron which was measured by DCP
NA – Not analyzed (SUM includes target fluorine value)

Table 2.33. Descriptions of Twelve As-Melted and Heat Treated ORPLG Crucible Glasses.

Glass ID	As-melted glass	Glass remelted at 1200°C for 1 hour, heat treated for 20 hours at 950°C, and quenched.
ORPLG1	Mostly clear glass. ~0.1 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.2 vol% tiny Cr oxide crystals
ORPLG2	Mostly clear glass. ~0.1 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.2 vol% tiny Cr oxide crystals
ORPLG3	Mostly clear glass. ~0.1 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.2 vol% tiny Cr oxide crystals
ORPLG4	Mostly clear glass. ~0.2 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.2 vol% tiny Cr oxide crystals
ORPLG5	Mostly clear glass. ~0.1 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.2 vol% tiny Cr oxide crystals
ORPLG6	Mostly clear glass. ~0.1 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.2 vol% tiny Cr oxide crystals
ORPLG7	Clear glass. <<0.1 vol% Cr-Zn oxide crystals	Mostly clear glass. ~0.2-0.3 vol% tiny Cr oxide crystals
ORPLG8	Clear glass. <<0.1 vol% Cr-Zn oxide crystals	Mostly clear glass. ~0.2-0.3 vol% tiny Cr oxide crystals
ORPLG9	Clear glass. <<0.1 vol% Cr-Zn oxide crystals	Mostly clear glass. ~0.2-0.3 vol% tiny Cr oxide crystals
ORPLG10	Clear glass. <<0.1 vol% Cr-Zn oxide crystals	Mostly clear glass. ~0.2 vol% tiny Cr oxide & NaZrSn silicate crystals
ORPLG11	Clear glass. <<0.1 vol% Cr-Zn oxide crystals	Mostly clear glass. ~0.2 vol% tiny Cr oxide & NaZrSn silicate crystals
ORPLG12	Mostly clear glass. ~0.1 vol% tiny Cr oxide crystals	Mostly clear glass. ~0.1 vol% tiny Cr oxide crystals

Table 2.34. Measured Sulfate Solubility Limits in Twelve ORPLG Crucible Glasses.

Sample ID	SO ₃ Content (wt%)		
	Batch Saturation		Bubbling*
	As-Melted	After Acid Wash	
ORPLG1S4	0.38	0.36	-
ORPLG2S4	0.40	0.38	-
ORPLG3S4	0.40	0.40	-
ORPLG4S4	0.44	0.43	-
ORPLG5S4	0.41	0.40	-
ORPLG6S4	0.47	0.45	-
ORPLG7S4	0.46	0.44	-
ORPLG8S4	0.49	0.46	-
ORPLG9S4	0.52	0.48	0.65 (sulfate layer onset at 0.31 wt% SO ₃)
ORPLG9CrS4 ^{\$}	-	-	0.55 (sulfate layer onset at 0.17 wt% SO ₃)
ORPLG10S4	0.54	0.49	-
ORPLG11S4	0.49	0.48	-
ORPLG12S4	0.50	0.47	-

- Empty data field

* Starting glass for bubbling tests contained no SO₃.

^{\$} Additional 0.4 wt% Cr₂O₃ was added to this glass – sulfate layer was observed immediately upon bubbling at SO₃ concentration of 0.17 wt% in the glass.

Table 2.35. Results of 7-day PCT (at 90°C) and VHT (at 200°C for 24 Days) for Twelve ORPLG Crucible Glasses.

Glass ID	ORPLG1	ORPLG2	ORPLG3	ORPLG4	ORPLG5	ORPLG6	ORPLG7	ORPLG8	ORPLG9	ORPLG10	ORPLG11	ORPLG12
7-Day PCT, Stainless Steel Vessel; S/V=2000m⁻¹ (ppm)												
B	13.06	42.17	24.40	25.89	15.48	16.23	16.64	16.09	27.42	25.48	29.38	39.18
Na	87.99	267.00	196.70	191.10	121.60	127.70	132.90	131.10	172.50	168.40	185.80	238.50
Si	46.65	84.53	74.25	86.53	49.27	49.69	55.52	51.92	63.57	65.68	69.84	79.60
Normalized Concentrations (g/L)												
B	0.47	1.62	0.92	0.97	0.57	0.60	0.61	0.59	1.02	0.95	1.10	1.49
Na	0.64	1.67	1.29	1.26	0.86	0.88	0.92	0.91	1.18	1.13	1.22	1.53
Si	0.24	0.45	0.39	0.45	0.26	0.26	0.29	0.27	0.32	0.34	0.36	0.42
pH	11.18	11.78	11.68	11.52	11.32	11.42	11.42	11.45	11.60	11.52	11.58	11.68
7-Day PCT Normalized Mass Loss (g/m²)												
B	0.24	0.81	0.46	0.49	0.29	0.30	0.31	0.30	0.51	0.47	0.55	0.74
Na	0.32	0.84	0.65	0.63	0.43	0.44	0.46	0.45	0.59	0.57	0.61	0.77
Si	0.12	0.22	0.19	0.22	0.13	0.13	0.15	0.14	0.16	0.17	0.18	0.21
7-Day PCT Normalized Loss Rate (g/m²/d)												
B	0.03	0.12	0.07	0.07	0.04	0.04	0.04	0.04	0.07	0.07	0.08	0.11
Na	0.05	0.12	0.09	0.09	0.06	0.06	0.07	0.06	0.08	0.08	0.09	0.11
Si	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03
VHT Alteration (24 days at 200°C)												
Alteration Depth (μm)	17	22	105	185	36	102	98 to 200	231 to 400	370 to 450	766 to 825	78	725 to 925
Alteration Rate (g/m ² /day)*	2	2	12	20	4	11	11 to 22	26 to 44	41 to 50	85 to 91	9	80 to 102

* Alteration rates calculated using estimated density of 2.65 g/cc

Table 2.36. Viscosities and Electrical Conductivities of Eleven ORPLG Crucible Glasses.

Glass ID	ORPLG1	ORPLG2	ORPLG4	ORPLG5	ORPLG6	ORPLG7	ORPLG8	ORPLG9	ORPLG10	ORPLG11	ORPLG12
Viscosity (poise)											
900°C	7260	6099	5159	4732	3072	3348	2153	1795	1444	2167	1630
950°C	2554	2169	1736	1664	1040	1173	840	702	580	796	675
1000°C	1041	891	707	693	430	483	373	315	264	342	314
1050°C	477	410	333	329	207	226	184	158	133	166	161
1100°C	241	208	176	173	111	117	99	86	73	89	89
1150°C	132	114	101	99	66	66	57	51	43	52	53
1200°C	77	67	63	61	42	39	35	32	26	32	33
1250°C	48	41	41	39	28	25	22	21	17	21	22
Electrical Conductivity (S/cm)											
900°C	0.078	0.074	0.124	0.115	0.129	0.133	0.190	0.148	0.142	0.139	0.150
950°C	0.117	0.116	0.163	0.156	0.168	0.171	0.233	0.224	0.198	0.196	0.208
1000°C	0.162	0.163	0.208	0.204	0.213	0.215	0.282	0.304	0.265	0.258	0.274
1050°C	0.210	0.215	0.259	0.258	0.266	0.265	0.336	0.385	0.344	0.323	0.347
1100°C	0.260	0.269	0.315	0.317	0.326	0.323	0.395	0.464	0.434	0.390	0.427
1150°C	0.312	0.324	0.377	0.380	0.394	0.388	0.459	0.539	0.535	0.457	0.512
1200°C	0.364	0.380	0.443	0.448	0.471	0.460	0.529	0.611	0.646	0.523	0.602
1250°C	0.416	0.435	0.513	0.519	0.556	0.539	0.603	0.678	0.768	0.589	0.695

Table 2.37. Results of K-3 Corrosion Testing for Eight ORPLG Crucible Glasses.

Glass ID	Neck loss (inches)	Depth of altered zone (inches)	Half-down loss (inches)
ORPLG5	0.0160	0.027	0.001
ORPLG6	0.0225	0.026	Coupon expanded – no measurable loss
ORPLG7	0.0265	0.027	Coupon expanded – no measurable loss
ORPLG8	0.0360	0.0255	Coupon expanded – no measurable loss
ORPLG9	0.0380	0.040	Coupon expanded – no measurable loss at half down but a large crack in this coupon's half down region which resulted in part of the coupon falling into the molten glass
ORPLG10	0.0415	0.023	0.0025
ORPLG11	0.0600	0.025	0.0005
ORPLG12	0.0245	0.024	Coupon expanded – no measurable loss

Table 2.38. Summary of Test Results for Selected ORPLG Glass Formulation ORPLG9 and Comparison to ILAW Requirements.

Test	Requirement [53, 54]	Test Result for ORPLG9
Density of glass	< 3.7 g/cc	2.56 g/cc
Crystalline Phase	Phase identification	Clear glass. << 0.1 vol% of small Cr crystals
Liquidus	< 950°C	< 950°C
Centerline Canister Cooling	Phase identification	Not measured
PCT B (g/m ²)	< 2.0 g/m ²	0.51 g/m ²
PCT Na (g/m ²)	< 2.0 g/m ²	0.59 g/m ²
PCT Si (g/m ²)	< 2.0 g/m ²	0.16 g/m ²
VHT at 200°C (g/m ² /day)	< 50 g/m ² /day	41 to 50 g/m ² /day (variations in the hydration thickness)
Viscosity (poise) at 1100°C	10 to 150 P	128 P
Conductivity (S/cm) at 1100°C	0.2 to 0.7 S/cm	0.445 S/cm
T _G (°C)	Report for modeling	Not measured

*Density measured for melter glass 10A-G-43B of the ORPLG9 composition

Table 2.39. Oxide Composition of AP-101 Simulant and ORPLG9 Glass Composition Used in Melter Tests (wt%).

Component	AP-101 waste contribution	Glass former additives	ORPLG9 (for AP-101)
Loading	29.10%	70.90%	-
Al ₂ O ₃	1.540	5.22	6.76
B ₂ O ₃	0.003	8.51	8.51
CaO	-	2.70	2.70
Cr ₂ O ₃	0.093	0.50	0.59
Fe ₂ O ₃	-	0.20	0.20
K ₂ O	5.755	-	5.76
MgO	-	0.96	0.96
Na ₂ O ^(a)	20.210 + 0.155 ⁽¹⁾ + 0.635 ⁽²⁾	-	21.00
NiO	0.009		0.01
PbO	0.009		0.01
SiO ₂	0.028	40.89	40.92
SnO ₂	-	2.84	2.84
ZnO	-	3.40	3.40
ZrO ₂	-	5.68	5.68
Cl	0.231	-	0.23
F	0.092	-	0.09
P ₂ O ₅	0.142	-	0.14
SO ₃ ^(b)	0.200 ⁽¹⁾	-	0.20
SUM	29.1	70.90	100.0

(a) Simulant was ordered at a concentration of 20.21 wt% Na₂O and modified before each melter test with (1) Na₂SO₄ and (2) NaOH additions to obtain 21.0 wt% Na₂O in the glass.

(b) Concentration of SO₃ was varied in steps during the melter tests.

– Empty data field

Table 2.40a. Glass Former Additives for 1 Liter of AP-101 Simulant (8.45 M Na) and Corresponding Melter Feed Properties.

Additives Source	Feed ORPLG9
Additives in Glass (wt%)	70.9
Kyanite (Al_2SiO_5) 325 Mesh (Kyanite Mining) (g)	106.81
H_3BO_3 (US Borax – Technical Granular) (g)	177.96
Wollastonite NYAD 325 Mesh (NYCO Minerals) (g)	69.87
Cr_2O_3 oxide	5.99
Olivine (Mg_2SiO_4) 325 Mesh (#180 Unimin) (g)	22.47
SiO_2 (Sil-co-Sil 75 US Silica) (g)	357.13
SnO_2 - Stannous Oxide - Mason color	33.54
ZnO (KADOX – 920 Zinc Corp. of America) (g)	40.07
Zircon ZrSiO_4 (Flour) Mesh 325 (AM. Mineral) (g)	100.86
Na_2SO_4	Variable – Table 2.40b
Addition of Sucrose as Reductant (g)	83.66
Simulant Weight for 1 liter (g)	1348
Sum of Additives (g)	998
Sum of Complete Batch (g)	2346
Target Final Volume (l)	1.35
Estimated Density (g/ml)	1.70
Target Glass Produced (g)	1181
Target Weight % Additives in Slurry	39
Target Glass Yield (g/kg of Feed)	503
Target Glass Yield (g/l of Feed)	875
Target Total Solids (g/l of Feed)	1126
Target Additives (g/l of Feed)	678

Table 2.40b. NaOH and Na_2SO_4 Additions Required to Obtain 21.0 wt% Na_2O and Various SO_3 Concentrations in the ORPLG9 Glass.

Final SO_3 wt%	NaOH needed per kg of feed (grams)	Na_2SO_4 needed per kg of feed (grams)
0.0	10.39	-
0.1	9.37	0.92
0.2	8.35	1.83
0.3	6.31	2.75

Table 2.41. Characteristics of Melter Feed Samples During DM10 ORP LAW Tests.

Tank Waste/ Sub-Envelope Identification	Test	Date	Name	Water (wt%)	pH	Density (g/ml)	Glass Yield			
							(g/l)	Measured (kg/kg)	Target (kg/kg)	%Dev.
AN-105/ Sub-Envelope A1	A	10/17/08	Z10-F-11A	42.29	13.17	1.66	566	0.341	0.470	-27.51
		Average (LAWA187) [6]		42.37	11.83	1.64	725	0.442		
		Average (LAWA161) [2]		38.70	11.50	1.68	791	0.472		
		High Temperature Test Average [3]		38.40	11.96	1.69	788	0.467		
		DM1200 Average [61]		37.60	12.19	1.72	827	0.481		
AN-102/ Sub-Envelope C2	D	10/24/08	Z10-F-61A	37.03	7.55	1.43	711	0.497	0.495	0.40
		1/13/09	Z10-F-146A	38.12	7.52	1.69	818	0.484	0.495	-2.16
		Average (LAWC31) [24]		39.31	9.13	1.67	765	0.466		
		DM1200 [62]*		38.5	8.95	1.69	821	0.485		
AZ-102/ Sub-Envelope B2	F	12/17/08	Z10-F-69A	39.94	13.00	1.71	915	0.535	0.559	-4.33
		1/8/08	Z10-F-123A	39.60	11.98	1.70	917	0.540	0.559	-3.47
		LAWB96 + 15% Simulant [22]		47.07	8.75	1.58	729	0.463		
		LAWB96 - 15% Simulant [22]		38.76	8.70	1.69	891	0.527		
		Average LAWB99 [6]		44.09	8.90	1.62	786	0.485		
AP-101/ Sub-Envelope A2	G	12/17/08	Z10-F-69B	37.28	NR	1.72	881	0.514	0.509	0.88
		1/8/09	Z10-F-129A	36.81	12.30	1.73	835	0.483	0.509	-5.17
		1/12/09	Z10-F-141A	36.05	12.77	1.75	868	0.496	0.509	-2.51
		1/16/09	10A-F-52A	35.66	13.39	1.75	865	0.494	0.509	-2.87
		DM1200 MACT [63]		35.40	12.25	1.74	885	0.505		
		Average LAWA126 [26]		36.01	12.50	1.73	820	0.474		

* This is an AN-107, Sub-Envelope C1 feed.

Table 2.42. Target and XRF Analyzed Composition of Vitrified Melter Feed Samples (wt%).

Test	A (ORPLA20)			D (ORPLD6)					
Sample Info	Composite Melter Feed			Melter Feed from Test 4			Composite Melter Feed		
Constituent	Target**	Z10-F-11A	%Dev.	Target	Z10-F-146A	%Dev.	Target**	Z10-F-61A	%Dev.
Al ₂ O ₃	6.65	6.54	-1.74	10.09	9.79	-3.02	10.11	10.19	0.86
B ₂ O ₃ *	8.74	8.74	NC	9.85	9.85	NC	9.86	9.86	NC
CaO	3.32	4.10	23.39	7.89	7.55	-4.38	7.90	7.41	-6.20
Cl	0.67	0.58	NC	0.35	0.20	NC	0.35	0.26	NC
Cr ₂ O ₃	0.50	0.70	NC	0.50	0.62	NC	0.50	0.62	NC
Cs ₂ O	§	<0.01	NC	§	<0.01	NC	§	<0.01	NC
F*	§	NA	NC	0.18	0.18	NC	0.18	0.18	NC
Fe ₂ O ₃	0.19	0.32	NC	0.28	0.38	NC	0.28	0.40	NC
I	§	0.08	NC	§	<0.01	NC	§	<0.01	NC
K ₂ O	0.53	0.52	NC	0.17	0.16	NC	0.17	0.20	NC
Li ₂ O	§	NA	NC	§	<0.01	NC	§	NA	NC
MgO	0.92	1.17	NC	1.00	0.75	NC	1.00	1.31	NC
MnO	§	0.01	NC	§	0.03	NC	§	<0.01	NC
Na ₂ O	24.00	22.57	-5.98	22.00	22.75	3.43	22.00	22.28	1.26
NiO	§	<0.01	NC	0.04	0.04	NC	0.04	0.05	NC
P ₂ O ₅	§	0.02	NC	0.30	0.40	NC	0.30	0.37	NC
PbO	§	<0.01	NC	0.01	0.02	NC	0.01	0.02	NC
SiO ₂	42.33	42.09	-0.58	37.24	37.12	-0.32	37.28	35.18	-5.62
SnO ₂	2.74	2.88	5.24	§	<0.01	NC	§	<0.01	NC
SO ₃	0.70	0.56	NC	1.20	1.03	NC	1.12	1.04	NC
TiO ₂	§	0.04	NC	§	0.20	NC	§	0.29	NC
V ₂ O ₅	§	0.03	NC	1.96	2.24	14.34	1.96	2.12	8.02
ZnO	2.74	2.86	4.51	2.96	3.07	3.84	2.96	2.93	-1.08
ZrO ₂	5.96	6.19	3.85	3.98	3.60	-9.48	3.99	5.30	33.03
Sum	100.00	100.00	NC	100.00	100.00	NC	100.00	100.00	NC

* - Target value for B₂O₃

** - Target composition calculated based on actual proportion of meter feed residues after test

§ - Not a target constituent

NA – Not analyzed

NC – Not calculated

Table 2.42. Target and XRF Analyzed Composition of Vitrified Melter Feed Samples (wt%) (continued).

Test	F (ORPLF7)					
Sample Info	Melter Feed Before Sulfur Addition			Melter Feed from Test F4		
Constituent	Target	Z10-F-69A	%Dev.	Target	Z10-F-123A	%Dev.
Al ₂ O ₃	8.92	8.79	-1.39	8.72	8.31	-4.76
B ₂ O ₃ *	9.85	9.85	NC	9.63	9.63	NC
CaO	10.08	9.22	-8.48	9.86	9.84	-0.12
Cl	0.01	0.02	NC	0.01	0.01	NC
Cr ₂ O ₃	0.58	0.81	NC	0.57	0.80	NC
Cs ₂ O	§	<0.01	NC	§	<0.01	NC
F*	0.07	0.07	NC	0.08	0.08	NC
Fe ₂ O ₃	0.24	0.34	NC	0.23	0.39	NC
I	§	<0.01	NC	§	<0.01	NC
K ₂ O	0.45	0.56	NC	0.50	0.53	NC
Li ₂ O*	4.51	4.51	NC	4.41	4.41	NC
MgO	1.02	1.05	3.48	0.99	1.16	NC
MnO	§	0.01	NC	§	0.01	NC
Na ₂ O	10.84	10.80	-0.38	12.00	11.54	-3.81
NiO	§	0.01	NC	§	<0.01	NC
P ₂ O ₅	0.03	0.08	NC	0.04	0.07	NC
PbO	§	<0.01	NC	§	<0.01	NC
SiO ₂	43.78	43.85	0.16	42.73	42.36	-0.89
SnO ₂	§	0.01	NC	§	0.01	NC
SO ₃	§	0.06	NC	0.80	0.92	NC
TiO ₂	§	0.22	NC	§	0.21	NC
V ₂ O ₅	2.59	2.87	10.88	2.53	2.90	14.34
ZnO	3.02	3.14	4.22	2.95	3.05	3.31
ZrO ₂	4.02	3.72	-7.65	3.93	3.78	-3.97
Sum	100.00	100.00	NC	100.00	100.00	NC

* - Target values

§ - Not a target constituent

NA – Not analyzed

NC – Not calculated

Table 2.42. Target and XRF Analyzed Composition of Vitrified Melter Feed Samples (wt%) (continued).

Test	G (ORPLG9)								
Sample Info	Melter Feed Before Sulfur Addition						Composite Melter Feed		
Constituent	Target	Z10-F-129A	Z10-F-141A	Z10-F-69B	Avg.	%Dev.	Target**	10A-F-52A	%Dev.
Al ₂ O ₃	6.79	6.04	6.44	6.53	6.34	-6.60	6.75	6.29	-6.82
B ₂ O ₃ *	8.62	8.62	8.62	8.62	8.62	NC	8.50	8.50	NC
CaO	2.73	2.85	2.76	1.86	2.49	-8.87	2.69	2.86	6.19
Cl	0.23	0.19	0.20	0.21	0.20	NC	0.23	0.18	NC
Cr ₂ O ₃	0.60	0.77	0.70	0.71	0.73	NC	0.59	0.68	NC
Cs ₂ O	§	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	NC
F*	0.09	0.09	0.09	0.09	0.09	NC	0.09	0.09	NC
Fe ₂ O ₃	0.20	0.17	0.27	0.23	0.22	NC	0.20	0.28	NC
I	§	0.10	0.11	0.11	0.10	NC	§	0.09	NC
K ₂ O	5.61	6.28	5.87	5.89	6.02	7.18	5.75	5.89	NC
Li ₂ O	§	NA	NA	NA	NA	NC	§	NA	NC
MgO	0.97	0.42	0.95	0.83	0.73	NC	0.95	0.82	NC
MnO	§	<0.01	<0.01	<0.01	<0.01	NC	§	<0.01	NC
Na ₂ O	20.52	21.55	19.83	22.65	21.34	4.02	21.00	20.36	-3.07
NiO	0.01	0.01	0.01	0.01	0.01	NC	0.01	0.01	NC
P ₂ O ₅	0.14	0.20	0.20	0.20	0.20	NC	0.14	0.20	NC
PbO	0.01	0.02	0.02	0.02	0.02	NC	0.01	0.01	NC
SiO ₂	41.43	41.02	41.37	40.26	40.88	-1.33	40.85	40.80	-0.12
SnO ₂	2.87	3.30	3.38	2.96	3.21	11.73	2.83	3.25	12.92
SO ₃	§	0.02	0.02	0.02	0.02	NC	0.33	0.25	NC
TiO ₂	§	0.10	0.12	0.12	0.11	NC	§	0.12	NC
V ₂ O ₅	§	<0.01	0.01	<0.01	0.01	NC	§	0.02	NC
ZnO	3.45	3.88	3.54	3.52	3.64	5.77	3.40	3.70	8.97
ZrO ₂	5.75	4.37	5.50	5.16	5.01	-12.86	5.67	5.56	-1.97
Sum	100.00	100.00	100.00	100.00	100.00	NC	100.00	100.00	NC

* - Target value

** - Target composition calculated based on actual proportion of meter feed residues after test

§ - Not a target constituent

NA – Not analyzed

NC – Not calculated

Table 3.1. Summary of Test A (Simulant: ORP S8AN105, Glass Formulation: ORPLA20) Conditions and Results.

Test Segment		A1	A2	A3	A4
Time	Feed Start	10/15/08 7:15	10/15/08 21:05	10/16/08 10:30	10/17/08 3:00
	Feed End	10/15/08 19:38	10/16/08 9:05	10/16/08 23:30	10/17/08 16:00
	Net Slurry Feeding (hr)	12.4	12.0	13.0	13.0
Feed	wt% SO ₃ as glass	0.5	0.7	0.9	0.8
	Feed Used (kg)	55.0	55.0	57.4	56.7
Average Production Rate (kg/m ² /day)*		2389	2462	2372	2344
Average Bubbling Rate (lpm)		3.3	3.5	3.9	3.5
Average Temperatures (°C)	Glass, 2" from floor	1152	1153	1153	1151
	Glass, 4" from floor	1122	1116	1126	1131
	Electrode	1093	1101	1093	1100
	Plenum, thermowell	469	471	492	476
	Plenum, exposed	428	411	445	436
Product	Secondary Phases on Melt Surface at Test End	No	No	Yes	Yes
	Measured wt% SO ₃	0.43	0.63	0.90	0.80
	% Feed Sulfur in Glass Product	86	90	100	100
Average Concentrations monitored in stack exhaust by FTIR (ppmv)	N ₂ O	68	68	67	65
	NO	574	580	570	550
	NO ₂	86	86	81	81
	CO	18	19	20	19
	NH ₃	25	33	29	27

* – Glass production rates calculated from feed data

**Table 3.2. Summary of Test D (Simulant: ORP S8AN102, Glass Formulation: ORPLD6)
Conditions and Results.**

Test Segment		D1	D2	D3	D4	D5
Time	Feed Start	10/21/08 22:20	10/22/08 12:45	10/23/08 2:28	10/23/08 19:25	1/15/09 19:40
	Feed End	10/22/08 11:30	10/23/08 1:30	10/23/08 17:30	10/24/0 7:50	1/16/09 11:26
	Net Slurry Feeding (hr)	13.2	12.8	15.1#	12.4	15.8
Feed	wt% SO ₃ as glass	0.9	1.1	1.3	1.2	1.2
	Feed Used (kg)	58.0	58.5	58.1	58.7	67.3
Average Production Rate (kg/m ² /day)*		2486	2541	2177	2678	2410
Average Bubbling Rate (lpm)		4.0	4.1	2.9	4.1	2.1
Average Temperatures (°C)	Glass, 2" from floor	1154	1151	1139	1152	1154
	Glass, 4" from floor	1138	1136	1125	1139	1147
	Electrode	1099	1097	1089	1100	1112
	Plenum, thermowell	533	465	502	471	514
	Plenum, exposed	502	407	442	422	431
Product	Secondary Phases on Melt Surface at Test End	No	No	Yes	No	Yes
	Measured wt% SO ₃	0.90	1.10	1.30	1.26	1.25
	% Feed Sulfur in Glass Product	100	100	100	105	104
Average Concentrations monitored in stack exhaust by FTIR (ppmv)	N ₂ O	121	123	132	135	74
	NO	632	657	699	725	621
	NO ₂	116	122	129	136	134
	CO	36	34	40	40	30
	NH ₃	42	46	43	53	41

* – Glass production rates calculated from feed data

– Net time reflects the total time interval including 130 minute down time.

NM – Not Measured.

Table 3.3. Summary of Test F (Simulant: ORP S5AZ102, Glass Formulation: ORPLF7) Conditions and Results.

Test Segment		F1	F2	F3	F4
Time	Feed Start	1/5/09 18:28	1/6/09 11:22	1/7/09 2:40	1/7/09 18:55
	Feed End	1/6/09 8:00	1/7/09 1:20	1/7/09 16:30	1/8/09 9:00
	Net Slurry Feeding (hr)	13.5	14.0	13.8	14.1
Feed	wt% SO ₃ as glass	1.6	1.4	1.2	0.8
	Feed Used (kg)	52.9	52.5	52.2	50.7
Average Production Rate (kg/m ² /day)*		2492	2396	2417	2297
Average Bubbling Rate (lpm)		1.8	2.2	2.0	2.6
Average Temperatures (°C)	Glass, 2" from floor	1155	1151	1153	1152
	Glass, 4" from floor	1147	1142	1143	1143
	Electrode	1105	1104	1108	1092
	Plenum, thermowell	516	513	494	468
	Plenum, exposed	503	497	467	451
Product	Secondary Phases on Melt Surface at Test End	Yes	Minor	No	No
	Measured wt% SO ₃	1.38	1.27	1.10	0.76
	% Feed Sulfur in Glass Product	86	91	92	95
Average Concentrations monitored in stack exhaust by FTIR (ppmv)	N ₂ O	< 1	< 1	< 1	< 1
	NO	64	62	61	58
	NO ₂	8	10	10	10
	CO	< 1	< 1	< 1	< 1
	NH ₃	< 1	< 1	< 1	< 1

* – Glass production rates calculated from feed data

@ – Net time reflects the total time interval including 112 minute down time.

NM – Not Measured.

Table 3.3. Summary of Test F (Simulant: ORP S5AZ102, Glass Formulation: ORPLF7) Conditions and Results (continued).

Test Segment		F5	F6
Time	Feed Start	1/12/09 12:01	1/13/09 2:15
	Feed End	1/13/09 0:50	1/13/09 14:45
	Net Slurry Feeding (hr)	12.8	12.5
Feed	wt% SO ₃ as glass	1.4	1.5
	Feed Used (kg)	48.3	47.5
Average Production Rate (kg/m ² /day)*		2411	2428
Average Bubbling Rate (lpm)		2.2	2.5
Average Temperatures (°C)	Glass, 2" from floor	1154	1153
	Glass, 4" from floor	1147	1146
	Electrode	1117	1115
	Plenum, thermowell	514	516
	Plenum, exposed	496	505
Product	Secondary Phases on Melt Surface at Test End	No	No
	Measured wt% SO ₃	1.20	1.35
	% Feed Sulfur in Glass Product	86	90
Average Concentrations monitored in stack exhaust by FTIR (ppmv)	N ₂ O	< 1	< 1
	NO	63	67
	NO ₂	3	4
	CO	< 1	< 1
	NH ₃	< 1	< 1

* – Glass production rates calculated from feed data

@ – Net time reflects the total time interval including 66 minute down time.

NC – Not Calculated.

Table 3.4. Summary of Test G (Simulant: ORP S8AP101, Glass Formulation: ORPLG9) Conditions and Results.

Test Segment		G1	G2	G3
Time	Feed Start	1/13/09 15:55	1/14/09 8:45	1/15/09 3:25
	Feed End	1/14/09 6:00	1/15/09 1:30	1/15/09 17:56
	Net Slurry Feeding (hr)	14.1	16.8	14.5
Feed	wt% SO ₃ as glass	0.5	0.3	0.2
	Feed Used (kg)	55.7	59.5	48.6
Average Production Rate (kg/m ² /day)*		2298	2060	1950
Average Bubbling Rate (lpm)		2.0	2.3	2.2
Average Temperatures (°C)	Glass, 2" from floor	1159	1154	1154
	Glass, 4" from floor	1154	1150	1150
	Electrode	1113	1103	1099
	Plenum, thermowell	531	486	486
	Plenum, exposed	502	429	402
Product	Secondary Phases on Melt Surface at Test End	Yes	Yes	Yes
	Measured wt% SO ₃	0.58	0.34	0.21
	% Feed Sulfur in Glass Product	116	113	105
Average Concentrations monitored in stack exhaust by FTIR (ppmv)	N ₂ O	62	55	55
	NO	518	437	426
	NO ₂	89	75	76
	CO	13	8	8
	NH ₃	20	26	25

* – Glass production rates calculated from feed data

NM – Not Measured.

Table 4.1. Listing of DM10 Glasses Discharged, Masses, Target Sulfur Contents and Analysis Performed.

Test	Formulation	Target SO ₃	Date	Name	Analysis	Mass (kg)	Cumulative Mass (kg)
A1	ORPLA20	0.5%	10/15/06	Y10-G-133A	-	-	-
				Y10-G-133B	-	-	-
				Y10-G-133C	XRF, DCP	4.34	4.34
				Y10-G-134A	-	-	-
				Y10-G-134B	-	-	-
				Y10-G-134C	XRF	4.12	8.46
				Y10-G-134D	-	-	-
				Y10-G-134E	-	-	-
				Y10-G-135A	XRF	6.42	14.88
				Y10-G-135B	-	-	-
				Y10-G-136A	-	-	-
				Y10-G-136B	XRF	4.32	19.20
				Y10-G-136C	-	-	-
				Y10-G-139A	XRF	3.86	23.06
A2		0.7%	10/16/08	Y10-G-139B	-	-	-
				Y10-G-142A	XRF	5.30	28.36
				Y10-G-142B	-	-	-
				Y10-G-143A	XRF	5.28	33.64
				Y10-G-143B	-	-	-
				Y10-G-143C	XRF	4.66	38.30
				Y10-G-146A	-	-	-
A3		0.9%	10/16/08	Y10-G-146B	XRF	4.36	42.66
				Y10-G-146C	XRF, DCP	2.36	45.02
				Y10-G-147A	-	-	-
				Y10-G-147B	XRF	4.92	49.94
				Y10-G-147C	-	-	-
				Y10-G-147D	XRF	5.36	55.30
				Y10-G-149A	-	-	-
				Y10-G-149B	XRF	3.62	58.92
				Y10-G-149C	-	-	-
				Y10-G-153A	XRF	4.20	63.12
A4		0.8%	10/17/08	Y10-G-153B	-	-	-
				Y10-G-153C	-	-	-
				Y10-G-153D	XRF	7.48	70.60
				Y10-G-155A	-	-	-
				Y10-G-155B	XRF	3.78	74.38
				Y10-G-5A	-	-	-
				Z10-G-5B	XRF	4.14	78.52
				Z10-G-5C	-	-	-
				Z10-G-5D	XRF	4.34	82.86
				Z10-G-5E	-	-	-
Z10-G-5F		XRF	4.04	86.90			
Z10-G-5G		-	-	-			
Z10-G-10A		XRF	4.26	91.16			

- Empty data field

Table 4.1. Listing of DM10 Glasses Discharged, Masses, Target Sulfur Contents and Analysis Performed (continued).

Test	Formulation	Target SO ₃	Date	Name	Analysis	Mass (kg)	Cumulative Mass (kg)
A4	ORPLA20	0.8%	10/17/08	Z10-G-10B	-	-	-
				Z10-G-11A	XRF	5.72	96.88
				Z10-G-16A	XRF	1.02	97.90
B1	ORPLD6	0.9%	10/21/08	Z10-G-29A	-	-	-
			10/22/08	Z10-G-29B	XRF	5.64	103.54
				Z10-G-29C	-	-	-
				Z10-G-30A	XRF	6.16	109.70
				Z10-G-31A	-	-	-
				Z10-G-34A	XRF	6.12	115.82
				Z10-G-34B	-	-	-
				Z10-G-34C	XRF	5.92	121.74
Z10-G-34D		XRF		2.18	123.92		
B2		1.1%	10/22/08	Z10-G-37A	-	-	-
				Z10-G-37B	XRF	7.10	131.02
				Z10-G-38A	-	-	-
				Z10-G-38B	XRF	5.44	136.46
				Z10-G-39A	-	-	-
				Z10-G-39B	XRF	5.02	141.48
				Z10-G-43A	-	-	-
				Z10-G-43B	XRF	4.54	146.02
B3		1.3%	10/23/08	Z10-G-43C	-	-	-
				Z10-G-44A	XRF	4.02	150.04
				Z10-G-45A	-	-	-
				Z10-G-46A	XRF	4.82	154.86
				Z10-G-46B	-	-	-
				Z10-G-46C	XRF	4.80	159.66
				Z10-G-50A	-	-	-
				Z10-G-50B	XRF	5.40	165.06
				Z10-G-51A	-	-	-
				Z10-G-51B	XRF	5.12	170.18
B4		1.2%	10/23/08	Z10-G-51C	-	-	-
				Z10-G-51D	XRF	5.68	175.86
				Z10-G-54A	-	-	-
				Z10-G-54B	XRF	5.00	180.86
			10/24/08	Z10-G-54C	-	-	-
				Z10-G-58A	XRF	4.36	185.22
				Z10-G-58B	-	-	-
				Z10-G-59A	XRF	5.62	190.84
				Z10-G-59B	-	-	-
				Z10-G-60A	XRF	5.38	196.22
			Z10-G-60B	-	-	-	
			Z10-G-60C	XRF,DCP	5.86	202.08	

- Empty data field

Table 4.1. Listing of DM10 Glasses Discharged, Masses, Target Sulfur Contents and Analysis Performed (continued).

Test	Formulation	Target SO ₃	Date	Name	Analysis	Mass (kg)	Cumulative Mass (kg)
B5	ORPLD6	1.2%	1/15/09	10A-G-45A	-	-	-
				10A-G-45B	XRF	4.44	206.52
				10A-G-51A	-	-	-
			1/16/09	10A-G-51B	XRF	5.30	211.82
				10A-G-51C	-	-	-
				10A-G-51D	XRF	4.10	215.92
				10A-G-52A	-	-	-
				10A-G-52B	XRF	4.12	220.04
				10A-G-52C	-	-	-
				10A-G-52D	XRF	3.88	223.92
				10A-G-52E	-	-	-
				10A-G-52F	XRF	3.26	227.18
				10A-G-53A	-	-	-
				10A-G-53B	XRF	3.80	230.98
				10A-G-53C	XRF	2.00	232.98
C1	ORPLF7	1.6%	1/5/09	Z10-G-85A	-	-	-
				Z10-G-85B	-	-	-
				Z10-G-86A	XRF,DCP	5.92	238.90
				Z10-G-86B	-	-	-
				Z10-G-86C	XRF	4.40	243.30
				Z10-G-89A	-	-	-
			1/6/09	Z10-G-89B	XRF	4.90	248.20
				Z10-G-89C	-	-	-
				Z10-G-89D	XRF	5.24	253.44
				Z10-G-89E	-	-	-
				Z10-G-90A	XRF	4.50	257.94
				Z10-G-90B	XRF	2.00	259.94
				Z10-G-95A	-	-	-
				Z10-G-95B	XRF	5.18	265.12
				Z10-G-97A	-	-	-
Z10-G-97B		XRF		5.08	270.20		
Z10-G-98A		-		-	-		
Z10-G-98B		XRF		4.42	274.62		
Z10-G-98C		-	-	-			
Z10-G-98D		XRF	4.48	279.10			
Z10-G-99A		-	-	-			
Z10-G-99B		XRF	4.24	283.34			
Z10-G-99C		-	-	-			
C3		1.2%	1/7/08	Z10-G-99D	XRF	3.90	287.24
				Z10-G-104A	-	-	-
				Z10-G-104B	XRF	4.70	291.94
				Z10-G-104C	-	-	-
	Z10-G-105A			XRF	3.92	295.86	

- Empty data field

Table 4.1. Listing of DM10 Glasses Discharged, Masses, Target Sulfur Contents and Analysis Performed (continued).

Test	Formulation	Target SO ₃	Date	Name	Analysis	Mass (kg)	Cumulative Mass (kg)	
C3	ORPLF7	1.2%	1/7/08	Z10-G-105B	-	-	-	
				Z10-G-105C	XRF	3.48	299.34	
				Z10-G-107A	-	-	-	
				Z10-G-107B	XRF	3.28	302.62	
				Z10-G-110A	-	-	-	
				Z10-G-110B	XRF	3.90	306.52	
				Z10-G-111A	-	-	-	
				Z10-G-111B	XRF	3.04	309.56	
				Z10-G-111C	XRF	2.28	311.84	
C4		0.8%	1/7/08	Z10-G-113A	-	-	-	
				Z10-G-113B	XRF	5.30	317.14	
				Z10-G-115A	-	-	-	
				Z10-G-115B	XRF	4.26	321.40	
			1/8/09	Z10-G-118A	-	-	-	
				Z10-G-118B	XRF	3.82	325.22	
				Z10-G-119A	-	-	-	
				Z10-G-119B	XRF	3.25	328.47	
				Z10-G-119C	-	-	-	
				Z10-G-121A	XRF	3.36	331.83	
C5		1.4%	1/8/09	Z10-G-121B	-	-	-	
				Z10-G-121C	XRF	3.42	335.25	
				Z10-G-122A	-	-	-	
				Z10-G-122B	XRF	2.38	337.63	
				1/12/09	Z10-G-141A	-	-	-
					Z10-G-141B	XRF, DCP	5.42	343.05
Z10-G-141C		-			-	-		
Z10-G-142A		XRF			4.86	347.91		
Z10-G-142B		-	-		-			
Z10-G-142C		XRF	6.06		353.97			
Z10-G-142D		-	-		-			
Z10-G-143A		XRF	4.48		358.45			
C6		1.5%	1/13/09	Z10-G-143B	XRF	2.08	360.53	
				Z10-G-146A	-	-	-	
				Z10-G-146B	XRF	5.50	366.03	
				Z10-G-148A	-	-	-	
				Z10-G-148B	XRF	4.68	370.71	
				Z10-G-148C	-	-	-	
				Z10-G-149A	XRF	5.62	376.33	
				Z10-G-149B	-	-	-	
	Z10-G-153A			XRF	5.92	382.25		
Z10-G-153B	XRF	5.38		387.63				
D1	ORPLG9	0.5%		10A-G-9A	-	-	-	
				10A-G-9B	XRF	4.08	391.71	

- Empty data field

Table 4.1. Listing of DM10 Glasses Discharged, Masses, Target Sulfur Contents and Analysis Performed (continued).

Test	Formulation	Target SO ₃	Date	Name	Analysis	Mass (kg)	Cumulative Mass (kg)
D1	ORPLG9	0.5%	1/13/09	10A-G-9C	-	-	-
				10A-G-14A	XRF	3.54	395.25
				10A-G-14B	-	-	-
				10A-G-14C	XRF	3.68	398.93
				10A-G-14D	-	-	-
			1/14/09	10A-G-15A	XRF	3.40	402.33
				10A-G-15B	-	-	-
				10A-G-15C	XRF	3.30	405.63
				10A-G-15D	-	-	-
				10A-G-18A	XRF	3.86	409.49
10A-G-18B		-		-	-		
10A-G-18C		XRF		3.08	412.57		
10A-G-21A		-		-	-		
10A-G-23A		XRF		2.50	415.07		
10A-G-23B		-		-	-		
10A-G-23C		XRF		2.88	417.95		
10A-G-23D		-		-	-		
10A-G-24A		XRF		2.68	420.63		
10A-G-24B		-		-	-		
10A-G-24C		XRF		2.00	422.63		
10A-G-24D		-	-	-			
10A-G-25A		XRF	3.30	425.93			
10A-G-25B		-	-	-			
10A-G-25C		XRF	3.44	429.37			
10A-G-29A		-	-	-			
10A-G-29B		XRF	3.42	432.79			
10A-G-29C		-	-	-			
10A-G-29D		XRF	2.78	435.57			
10A-G-30A		-	-	-			
D2		0.3%	1/14/09	10A-G-30B	XRF	2.84	438.41
	10A-G-32A			-	-	-	
	10A-G-33A			XRF	5.48	443.89	
	10A-G-33B			-	-	-	
	10A-G-36A			XRF	2.26	446.15	
	10A-G-36B			-	-	-	
	10A-G-37A			XRF	2.82	448.97	
	10A-G-38A			-	-	-	
	10A-G-38B			XRF	2.66	451.63	
	10A-G-38C			-	-	-	
	10A-G-38D			XRF	2.38	454.01	
	10A-G-38E			-	-	-	
	10A-G-38F			XRF	2.40	456.41	
	10A-G-39A			-	-	-	
	10A-G-39B			XRF	2.56	458.97	
D3	0.2%	1/15/09	10A-G-43A	-	-	-	
			10A-G-43B	XRF	3.94	462.91	

- Empty data field

Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%).

Formulation	ORPLA20									
Test	A1						A2			
Target SO ₃	0.5%						0.7%			
Glass (kg)	-	4.34	8.46	14.88	19.20	23.06	-	28.36	33.64	38.30
Constituent	Target	Y10-G-133C	Y10-G-134C	Y10-G-135A	Y10-G-136B	Y10-G-139A	Target	Y10-G-142A	Y10-G-143A	Y10-G-143C
Al ₂ O ₃	6.67	8.35	7.97	7.57	7.16	7.14	6.65	6.92	6.79	6.66
B ₂ O ₃	8.76	7.93	8.21	8.47	8.57	8.63	8.74	8.68	8.70	8.72
CaO	3.33	2.75	3.04	3.20	3.31	3.35	3.32	3.45	3.54	3.51
Cl	0.67	0.31	0.35	0.40	0.46	0.46	0.67	0.49	0.49	0.48
Cr ₂ O ₃ *	0.50	0.42	0.56	0.61	0.65	0.66	0.50	0.73	0.72	0.75
Cs ₂ O	§	0.11	0.06	0.03	0.01	<0.01	§	<0.01	<0.01	<0.01
F	§	NA	NA	NA	NA	NA	§	NA	NA	NA
Fe ₂ O ₃	0.19	3.12	2.20	1.48	0.95	0.71	0.19	0.59	0.47	0.37
I	§	0.06	0.07	0.09	0.09	0.09	§	0.13	0.12	0.11
K ₂ O	0.54	0.52	0.54	0.53	0.54	0.53	0.53	0.56	0.54	0.55
Li ₂ O*	§	0.13	0.09	0.05	0.03	0.02	§	0.01	0.01	<0.01
MgO	0.93	1.51	1.36	1.11	0.98	0.93	0.92	0.78	0.75	0.98
MnO	§	0.02	0.01	0.01	0.01	0.00	§	<0.01	0.01	0.01
Na ₂ O	24.00	20.65	21.49	22.62	23.34	22.87	24.00	23.51	23.11	23.78
NiO	§	0.46	0.35	0.26	0.18	0.14	§	0.14	0.13	0.14
P ₂ O ₅	§	0.34	0.23	0.15	0.10	0.08	§	0.07	0.05	0.04
PbO	§	<0.01	0.01	0.01	<0.01	<0.01	§	0.01	0.01	0.01
SiO ₂	42.44	43.68	42.86	42.53	42.75	43.82	42.33	42.42	42.19	41.98
SnO ₂	2.75	1.53	2.20	2.52	2.60	2.60	2.74	3.17	3.40	3.07
SO ₃	0.50	0.31	0.34	0.38	0.41	0.43	0.70	0.45	0.53	0.56
TiO ₂	§	0.40	0.28	0.19	0.12	0.10	§	0.08	0.07	0.05
V ₂ O ₅	§	0.42	0.27	0.17	0.10	0.07	§	0.05	0.03	0.01
ZnO	2.75	2.41	2.59	2.66	2.67	2.61	2.74	2.82	2.92	2.84
ZrO ₂	5.97	4.59	4.91	4.92	4.95	4.77	5.96	4.95	5.43	5.40
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“--” sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLA20										
Test	A2			A3						A4	
Target SO ₃	0.7%			0.9%						0.8%	
Glass (kg)	-	42.66	45.02	-	49.94	55.30	58.92	63.12	70.60	-	74.38
Constituent	Target	Y10-G-146B	Y10-G-146C	Target	Y10-G-147B	Y10-G-147D	Y10-G-149B	Y10-G-153A	Y10-G-153D	Target	Y10-G-155B
Al ₂ O ₃	6.65	6.59	6.72	6.64	6.82	6.70	6.66	6.62	6.52	6.64	6.55
B ₂ O ₃	8.74	8.72	8.73	8.72	8.72	8.72	8.72	8.72	8.72	8.73	8.72
CaO	3.32	3.56	3.56	3.31	3.45	3.39	3.42	3.38	3.50	3.32	3.48
Cl	0.67	0.50	0.53	0.67	0.46	0.47	0.49	0.49	0.54	0.67	0.45
Cr ₂ O ₃ *	0.50	0.72	0.73	0.50	0.68	0.67	0.68	0.67	0.76	0.50	0.68
Cs ₂ O	§	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01
F	§	NA	NA	§	NA	NA	NA	NA	NA	§	NA
Fe ₂ O ₃	0.19	0.34	0.35	0.19	0.28	0.27	0.27	0.29	0.28	0.19	0.28
I	§	0.10	0.10	§	0.09	0.11	0.10	0.10	0.10	§	0.10
K ₂ O	0.53	0.55	0.56	0.53	0.53	0.55	0.53	0.53	0.56	0.53	0.54
Li ₂ O*	§	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01
MgO	0.92	1.00	0.95	0.92	0.82	0.99	0.99	1.14	0.99	0.92	1.10
MnO	§	0.01	0.01		0.01	0.01	0.01	0.01	0.01	§	0.01
Na ₂ O	24.00	22.61	23.09	24.00	23.72	23.95	23.27	23.10	23.54	24.00	23.75
NiO	§	0.09	0.09	§	0.08	0.07	0.07	0.07	0.06	§	0.10
P ₂ O ₅	§	0.03	0.04	§	0.03	0.03	0.03	0.03	0.02	§	0.02
PbO	§	0.01	0.01	§	0.01	0.01	0.01	<0.01	0.01	§	<0.01
SiO ₂	42.33	42.62	42.78	42.22	42.98	42.46	42.84	42.83	41.63	42.28	42.38
SnO ₂	2.74	3.22	2.87	2.73	2.81	2.94	2.96	2.98	3.17	2.73	2.97
SO ₃	0.70	0.63	0.61	0.90	0.69	0.73	0.84	0.82	1.04	0.80	0.76
TiO ₂	§	0.05	0.05	§	0.04	0.03	0.04	0.04	0.04	§	0.04
V ₂ O ₅	§	0.01	0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01
ZnO	2.74	2.91	2.87	2.73	2.74	2.69	2.71	2.72	2.89	2.73	2.78
ZrO ₂	5.96	5.71	5.35	5.94	5.06	5.23	5.34	5.47	5.61	5.95	5.30
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“--” sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLA20							ORPLD6			
Test	A4							D1			
Target SO ₃	0.8%							0.9%			
Glass (kg)	-	78.52	82.86	86.90	91.16	96.88	97.90	-	103.54	109.70	115.82
Constituent	Target	Z10-G-5B	Z10-G-5D	Z10-G-5F	Z10-G-10A	Z10-G-11A	Z10-G-16A	Target	Z10-G-29B	Z10-G-30A	Z10-G-34A
Al ₂ O ₃	6.64	6.57	6.48	6.52	6.57	6.47	6.76	10.13	7.93	8.53	8.78
B ₂ O ₃	8.73	8.72	8.72	8.73	8.73	8.73	8.73	9.89	9.23	9.53	9.70
CaO	3.32	3.56	3.52	3.45	3.55	3.60	3.56	7.92	5.40	6.65	7.39
Cl	0.67	0.49	0.49	0.48	0.51	0.54	0.10	0.35	0.17	0.22	0.22
Cr ₂ O ₃ *	0.50	0.72	0.71	0.68	0.70	0.80	1.16	0.50	0.76	0.76	0.80
Cs ₂ O	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01	<0.01	<0.01
F	§	NA	NA	NA	NA	NA	NA	0.18	NA	NA	NA
Fe ₂ O ₃	0.19	0.30	0.31	0.27	0.29	0.28	0.53	0.28	0.44	0.43	0.38
I	§	0.10	0.12	0.11	0.10	0.10	0.10	§	0.07	0.03	0.02
K ₂ O	0.53	0.57	0.54	0.54	0.55	0.57	0.53	0.17	0.37	0.28	0.25
Li ₂ O*	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01	<0.01	<0.01
MgO	0.92	0.97	1.00	1.09	1.03	0.88	0.96	§	0.95	0.86	0.85
MnO	§	<0.01	0.01	0.01	0.01	0.01	0.01	§	<0.01	0.01	0.01
Na ₂ O	24.00	22.91	23.19	23.78	22.64	23.14	21.93	22.00	22.97	23.22	23.32
NiO	§	0.09	0.07	0.06	0.06	0.06	0.26	0.04	0.23	0.19	0.19
P ₂ O ₅	§	0.01	0.02	0.02	<0.01	0.03	0.05	0.30	0.18	0.26	0.32
PbO	§	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
SiO ₂	42.28	42.18	42.06	41.82	42.61	41.58	42.40	37.38	40.22	38.24	37.39
SnO ₂	2.73	3.27	3.31	3.17	3.22	3.42	3.30	§	1.88	0.99	0.50
SO ₃	0.80	0.82	0.83	0.79	0.79	0.93	1.13	0.90	0.76	0.80	0.85
TiO ₂	§	0.04	0.04	0.04	0.03	0.04	0.06	§	0.11	0.15	0.17
V ₂ O ₅	§	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	1.97	0.97	1.55	1.87
ZnO	2.73	2.94	2.88	2.83	2.89	2.99	2.89	2.97	2.86	2.99	3.06
ZrO ₂	5.95	5.72	5.69	5.60	5.73	5.83	5.51	4.00	4.50	4.28	3.91
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“-“ sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%),
(continued).**

Formulation	ORPLD6										
Test	D1			D2						D3	
Target SO ₃	0.9%			1.1%						1.3%	
Glass (kg)	-	121.74	123.92	-	131.02	136.46	141.48	146.02	150.04	-	154.86
Constituent	Target	Z10-G-34C	Z10-G-34D	Target	Z10-G-37B	Z10-G-38B	Z10-G-39B	Z10-G-43B	Z10-G-44A	Target	Z10-G-46A
Al ₂ O ₃	10.13	8.78	9.04	10.11	9.28	9.37	9.18	8.70	8.64	10.08	9.08
B ₂ O ₃	9.89	9.78	9.80	9.86	9.83	9.85	9.85	9.86	9.86	9.84	9.85
CaO	7.92	7.88	7.71	7.90	7.83	7.60	7.59	8.23	8.13	7.88	8.03
Cl	0.35	0.28	0.28	0.35	0.29	0.27	0.29	0.31	0.31	0.35	0.27
Cr ₂ O ₃ *	0.50	0.85	0.82	0.50	0.78	0.71	0.71	0.82	0.81	0.50	0.76
Cs ₂ O	§	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01
F	0.18	NA	NA	0.18	NA	NA	NA	NA	NA	0.18	NA
Fe ₂ O ₃	0.28	0.40	0.42	0.28	0.38	0.36	0.30	0.31	0.28	0.28	0.32
I	§	0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01
K ₂ O	0.17	0.24	0.22	0.17	0.21	0.19	0.21	0.22	0.21	0.17	0.21
Li ₂ O*	§	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01
MgO	§	0.75	0.82	1.00	0.87	0.90	0.82	0.70	0.60	1.00	0.68
MnO	§	0.01	0.01	§	<0.01	0.01	<0.01	0.01	0.01	§	0.01
Na ₂ O	22.00	22.96	23.87	22.00	22.85	23.41	24.43	23.75	24.49	22.00	23.24
NiO	0.04	0.19	0.19	0.04	0.18	0.16	0.17	0.19	0.20	0.04	0.22
P ₂ O ₅	0.30	0.36	0.35	0.30	0.37	0.37	0.38	0.38	0.40	0.30	0.38
PbO	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.02
SiO ₂	37.38	37.23	36.71	37.28	37.10	37.25	36.97	36.65	36.57	37.19	36.76
SnO ₂	§	0.31	0.19	§	0.08	0.06	0.04	0.04	0.04	§	0.04
SO ₃	0.90	0.90	0.87	1.10	0.96	1.02	1.02	1.07	1.14	1.30	1.18
TiO ₂	§	0.16	0.17	§	0.20	0.18	0.16	0.16	0.15	§	0.18
V ₂ O ₅	1.97	2.09	2.08	1.96	2.11	2.02	2.02	2.26	2.25	1.96	2.22
ZnO	2.97	3.20	3.03	2.96	2.99	2.81	2.79	3.22	3.15	2.96	3.10
ZrO ₂	4.00	3.59	3.43	3.99	3.70	3.44	3.05	3.10	2.73	3.98	3.46
Sum	10.13	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“-“ sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLD6										
Test	D3					D4					
Target SO ₃	1.3%					1.2%					
Glass (kg)	-	159.66	165.06	170.18	175.86	-	180.86	185.22	190.84	196.22	202.08
Constituent	Target	Z10-G-46C	Z10-G-50B	Z10-G-51B	Z10-G-51D	Target	Z10-G-54B	Z10-G-58A	Z10-G-59A	Z10-G-60A	Z10-G-60C
Al ₂ O ₃	10.08	9.22	9.19	9.21	9.26	10.09	9.24	9.20	9.14	8.97	8.73
B ₂ O ₃	9.84	9.85	9.84	9.84	9.84	9.85	9.84	9.85	9.85	9.85	9.85
CaO	7.88	8.05	7.89	7.95	7.92	7.89	7.98	8.06	8.11	8.08	8.29
Cl	0.35	0.28	0.30	0.30	0.30	0.35	0.25	0.27	0.29	0.31	0.31
Cr ₂ O ₃ *	0.50	0.77	0.78	0.72	0.71	0.50	0.76	0.77	0.79	0.77	0.85
Cs ₂ O	§	<0.01	<0.01	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01
F	0.18	NA	NA	NA	NA	0.18	NA	NA	NA	NA	NA
Fe ₂ O ₃	0.28	0.36	0.36	0.33	0.33	0.28	0.34	0.36	0.36	0.29	0.58
I	§	<0.01	<0.01	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01
K ₂ O	0.17	0.21	0.20	0.21	0.20	0.17	0.20	0.21	0.21	0.20	0.22
Li ₂ O*	§	<0.01	<0.01	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01
MgO	1.00	0.80	0.82	0.79	0.75	1.00	0.74	0.81	0.82	0.63	0.52
MnO	§	0.01	0.01	0.01	<0.01	§	0.01	0.01	0.01	<0.01	0.01
Na ₂ O	22.00	23.06	23.36	23.39	23.33	22.00	23.10	23.07	22.62	23.26	23.17
NiO	0.04	0.22	0.22	0.18	0.18	0.04	0.23	0.23	0.22	0.21	0.24
P ₂ O ₅	0.30	0.37	0.37	0.38	0.37	0.30	0.37	0.37	0.37	0.39	0.39
PbO	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02
SiO ₂	37.19	36.52	36.37	36.48	36.68	37.24	36.61	36.33	36.74	37.10	36.80
SnO ₂	§	0.03	0.03	0.02	0.02	§	0.03	0.02	0.02	0.02	0.02
SO ₃	1.30	1.23	1.32	1.29	1.27	1.20	1.25	1.26	1.26	1.25	1.26
TiO ₂	§	0.19	0.19	0.19	0.19	§	0.19	0.19	0.19	0.17	0.16
V ₂ O ₅	1.96	2.18	2.15	2.16	2.15	1.96	2.18	2.21	2.20	2.22	2.27
ZnO	2.96	3.08	3.00	2.99	2.99	2.96	3.03	3.10	3.11	3.08	3.21
ZrO ₂	3.98	3.57	3.59	3.54	3.50	3.98	3.63	3.67	3.67	3.17	3.11
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“--” sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLD6									ORPLF7	
Test	D5									F1	
Target SO ₃	1.2%									1.6%	
Glass (kg)	-	206.52	211.82	215.92	220.04	223.92	227.18	230.98	232.98	-	238.90
Constituent	Target	10A-G-45B	10A-G-51B	10A-G-51D	10A-G-52B	10A-G-52D	10A-G-52F	10A-G-53B	10A-G-53C	Target	Z10-G-86A
Al ₂ O ₃	10.09	7.57	8.63	8.84	9.46	9.64	9.74	9.70	9.61	8.64	7.12
B ₂ O ₃	9.85	8.97	9.33	9.51	9.62	9.70	9.74	9.77	9.79	9.54	8.88
CaO	7.89	4.23	5.44	5.98	6.74	7.13	7.32	7.34	7.41	9.77	5.10
Cl	0.35	0.18	0.19	0.21	0.21	0.23	0.22	0.23	0.24	0.01	0.08
Cr ₂ O ₃ *	0.50	0.81	0.76	0.77	0.75	0.74	0.75	0.75	0.79	0.56	0.48
Cs ₂ O	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	§	0.07
F	0.18	NA	NA	NA	NA	NA	NA	NA	NA	0.08	NA
Fe ₂ O ₃	0.28	0.33	0.38	0.43	0.44	0.43	0.42	0.40	0.82	0.23	4.41
I	§	0.07	0.04	0.04	0.02	0.01	<0.01	0.01	0.01	§	<0.01
K ₂ O	0.17	3.90	2.40	1.95	1.02	0.69	0.53	0.43	0.37	0.50	0.45
Li ₂ O*	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	4.37	1.79
MgO	1.00	0.92	1.00	0.92	1.04	0.95	0.90	0.81	0.81	0.98	1.60
MnO	§	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.03	§	0.02
Na ₂ O	22.00	21.82	21.98	21.31	21.76	21.55	21.64	22.34	21.94	12.00	16.95
NiO	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	§	0.21
P ₂ O ₅	0.30	0.24	0.30	0.32	0.36	0.37	0.38	0.39	0.39	0.04	0.07
PbO	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.02	§	<0.01
SiO ₂	37.24	39.36	38.51	38.39	37.84	37.70	37.46	37.19	37.02	42.34	43.14
SnO ₂	§	2.15	1.27	1.06	0.47	0.30	0.21	0.15	0.13	§	0.02
SO ₃	1.20	0.49	0.76	0.86	1.02	1.13	1.12	1.23	1.25	1.60	0.81
TiO ₂	§	0.15	0.17	0.19	0.20	0.21	0.21	0.20	0.20	§	0.51
V ₂ O ₅	1.96	0.72	1.30	1.52	1.85	2.03	2.11	2.14	2.16	2.51	1.96
ZnO	2.96	3.27	3.11	3.23	3.06	3.11	3.15	3.07	3.11	2.92	3.06
ZrO ₂	3.98	4.76	4.33	4.40	4.04	3.98	4.00	3.77	3.88	3.90	3.28
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“-“ sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLF7										
Test	F1						F2				
Target SO ₃	1.6%						1.4%				
Glass (kg)	-	243.30	248.20	253.44	257.94	259.94	-	265.12	270.20	274.62	279.10
Constituent	Target	Z10-G-86C	Z10-G-89B	Z10-G-89D	Z10-G-90A	Z10-G-90B	Target	Z10-G-95B	Z10-G-97B	Z10-G-98B	Z10-G-98D
Al ₂ O ₃	8.64	7.52	7.73	7.80	7.88	8.04	8.66	7.94	8.10	8.09	8.07
B ₂ O ₃	9.54	9.12	9.28	9.39	9.45	9.46	9.57	9.50	9.53	9.54	9.55
CaO	9.77	6.78	7.68	8.50	9.08	9.21	9.79	9.45	9.76	9.71	9.90
Cl	0.01	0.06	0.03	0.03	0.02	0.02	0.01	0.01	0.02	0.02	0.02
Cr ₂ O ₃ *	0.56	0.58	0.65	0.71	0.74	0.74	0.56	0.76	0.77	0.77	0.78
Cs ₂ O	§	0.05	<0.01	0.02	0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01
F	0.08	NA	NA	NA	NA	NA	0.08	NA	NA	NA	NA
Fe ₂ O ₃	0.23	2.89	2.11	1.54	1.19	0.94	0.23	0.84	0.67	0.59	0.56
I	§	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01
K ₂ O	0.50	0.48	0.48	0.50	0.50	0.50	0.50	0.52	0.53	0.52	0.54
Li ₂ O*	4.37	2.71	3.35	3.77	3.99	4.06	4.38	4.19	4.26	4.31	4.33
MgO	0.98	1.38	1.29	1.20	1.13	1.10	0.99	1.07	1.01	1.02	1.03
MnO	§	0.01	0.01	0.01	0.01	0.01	§	0.01	0.01	0.01	0.01
Na ₂ O	12.00	15.30	14.35	13.53	12.76	12.18	12.00	12.35	11.80	12.17	11.78
NiO	§	0.15	0.11	0.08	0.06	0.05	§	0.05	0.04	0.03	0.03
P ₂ O ₅	0.04	0.07	0.08	0.07	0.06	0.07	0.04	0.08	0.07	0.07	0.08
PbO	§	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01	0.02	<0.01	<0.01
SiO ₂	42.34	42.83	42.52	42.02	42.41	42.75	42.44	42.14	42.27	42.30	42.18
SnO ₂	§	0.02	0.01	0.02	0.01	0.01	§	0.01	0.02	0.01	0.01
SO ₃	1.60	1.06	1.15	1.26	1.34	1.38	1.40	1.29	1.26	1.27	1.26
TiO ₂	§	0.40	0.34	0.29	0.26	0.24	§	0.23	0.22	0.21	0.21
V ₂ O ₅	2.51	2.22	2.38	2.56	2.63	2.65	2.52	2.73	2.80	2.75	2.80
ZnO	2.92	2.95	2.95	3.00	2.95	2.94	2.93	3.00	3.02	2.91	3.03
ZrO ₂	3.90	3.44	3.50	3.70	3.51	3.66	3.91	3.80	3.81	3.71	3.84
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“-“ sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLF7										
Test	F2			F3							
Target SO ₃	1.4%			1.2%							
Glass (kg)	-	283.34	287.24	-	291.94	295.86	299.34	302.62	306.52	309.56	311.84
Constituent	Target	Z10-G-99B	Z10-G-99D	Target	Z10-G-104B	Z10-G-105A	Z10-G-105C	Z10-G-107B	Z10-G-110B	Z10-G-111B	Z10-G-111C
Al ₂ O ₃	8.66	8.06	8.07	8.68	8.19	8.12	8.24	8.22	8.20	8.15	8.12
B ₂ O ₃	9.57	9.56	9.56	9.59	9.57	9.58	9.58	9.58	9.58	9.59	9.59
CaO	9.79	10.15	9.90	9.81	9.89	9.99	9.94	9.89	9.91	10.03	9.94
Cl	0.01	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01
Cr ₂ O ₃ *	0.56	0.80	0.79	0.57	0.79	0.80	0.79	0.79	0.79	0.81	0.81
Cs ₂ O	§	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
F	0.08	NA	NA	0.08	NA	NA	NA	NA	NA	NA	NA
Fe ₂ O ₃	0.23	0.46	0.44	0.23	0.40	0.43	0.56	0.49	0.45	0.38	0.46
I	§	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
K ₂ O	0.50	0.54	0.53	0.50	0.54	0.53	0.52	0.52	0.52	0.54	0.53
Li ₂ O*	4.38	4.35	4.36	4.39	4.37	4.38	4.38	4.38	4.39	4.39	4.39
MgO	0.99	1.04	0.95	0.99	1.00	1.00	1.04	1.04	1.05	1.02	0.96
MnO	§	0.01	0.01	§	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Na ₂ O	12.00	11.46	12.26	12.00	12.04	11.69	11.45	11.84	12.13	11.98	11.47
NiO	§	0.02	0.02	§	0.02	0.02	0.02	0.02	0.02	0.02	0.02
P ₂ O ₅	0.04	0.08	0.08	0.04	0.07	0.07	0.07	0.07	0.08	0.07	0.06
PbO	§	<0.01	<0.01	§	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SiO ₂	42.44	42.18	42.13	42.54	42.21	42.30	42.53	42.23	42.15	42.26	42.66
SnO ₂	§	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01
SO ₃	1.40	1.28	1.27	1.20	1.21	1.17	1.15	1.09	1.11	1.10	1.10
TiO ₂	§	0.21	0.20	§	0.20	0.20	0.20	0.20	0.20	0.20	0.19
V ₂ O ₅	2.52	2.90	2.81	2.52	2.77	2.85	2.82	2.78	2.78	2.83	2.87
ZnO	2.93	3.06	2.99	2.94	2.93	3.02	2.95	2.98	2.98	3.01	3.05
ZrO ₂	3.91	3.82	3.59	3.92	3.73	3.81	3.73	3.83	3.62	3.59	3.76
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“-“ sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLF7										
Test	F4								F5**		
Target SO ₃	0.8%								1.4%		
Glass (kg)	-	317.14	321.40	325.22	328.47	331.83	335.25	337.63	-	343.05	347.91
Constituent	Target	Z10-G-113B	Z10-G-115B	Z10-G-118B	Z10-G-119B	Z10-G-121A	Z10-G-121C	Z10-G-122B	Target	Z10-G-141B	Z10-G-142A
Al ₂ O ₃	8.72	8.09	8.20	8.26	8.21	8.20	8.31	8.18	8.66	7.99	8.08
B ₂ O ₃	9.63	9.61	9.61	9.62	9.62	9.63	9.63	9.63	9.57	9.12	9.29
CaO	9.86	9.88	9.72	9.69	9.82	10.07	9.71	9.95	9.79	7.73	8.52
Cl	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.01
Cr ₂ O ₃ *	0.57	0.80	0.79	0.78	0.80	0.82	0.77	0.81	0.56	0.70	0.73
Cs ₂ O	§	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	§	0.02	0.02
F	0.08	NA	NA	NA	NA	NA	NA	NA	0.08	NA	NA
Fe ₂ O ₃	0.23	0.41	0.38	0.37	0.39	0.38	0.42	0.43	0.23	2.03	1.38
I	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01	<0.01
K ₂ O	0.50	0.54	0.52	0.52	0.51	0.53	0.51	0.53	0.50	0.51	0.52
Li ₂ O*	4.41	4.40	4.40	4.40	4.41	4.41	4.41	4.41	4.38	3.23	3.67
MgO	0.99	0.95	1.04	1.01	1.06	1.02	1.02	1.00	0.99	1.29	1.16
MnO	§	0.01	0.01	0.01	0.01	0.01	0.01	0.01	§	0.02	0.02
Na ₂ O	12.00	11.75	12.05	11.99	11.77	11.53	12.33	11.74	12.00	14.32	13.81
NiO	§	0.02	0.01	0.02	0.02	0.02	0.01	0.01	§	0.02	0.02
P ₂ O ₅	0.04	0.08	0.07	0.08	0.07	0.07	0.07	0.08	0.04	0.08	0.07
PbO	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01	<0.01
SiO ₂	42.73	42.63	42.73	43.01	42.81	42.44	42.57	42.63	42.44	42.98	42.26
SnO ₂	§	<0.01	<0.01	0.01	0.01	0.01	<0.01	0.01	§	0.02	0.02
SO ₃	0.80	1.08	0.92	0.85	0.81	0.79	0.77	0.76	1.40	1.00	1.10
TiO ₂	§	0.20	0.19	0.19	0.20	0.20	0.20	0.19	§	0.32	0.27
V ₂ O ₅	2.53	2.83	2.75	2.74	2.80	2.94	2.73	2.85	2.52	2.44	2.55
ZnO	2.95	2.98	2.90	2.89	2.98	3.11	2.91	3.03	2.93	2.94	2.93
ZrO ₂	3.93	3.73	3.67	3.54	3.68	3.79	3.61	3.74	3.91	3.23	3.56
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“-“ sign for empty data field

** Turnover proceeded before this test

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLF7									
Test	F5				F6					
Target SO ₃	1.4%				1.5%					
Glass (kg)	-	353.97	358.45	360.53	-	366.03	370.71	376.33	382.25	387.63
Constituent	Target	Z10-G-142C	Z10-G-143A	Z10-G-143B	Target	Z10-G-146B	Z10-G-148B	Z10-G-149A	Z10-G-153A	Z10-G-153B
Al ₂ O ₃	8.66	8.11	8.16	8.12	8.65	8.24	8.27	8.33	8.36	8.37
B ₂ O ₃	9.57	9.42	9.47	9.49	9.56	9.52	9.53	9.54	9.55	9.55
CaO	9.79	9.06	9.07	9.35	9.78	9.52	9.61	9.52	9.63	9.66
Cl	0.01	<0.01	0.01	0.03	0.01	0.01	0.02	0.01	0.01	0.01
Cr ₂ O ₃ *	0.56	0.77	0.77	0.77	0.56	0.83	0.81	0.79	0.80	0.80
Cs ₂ O	§	<0.01	0.01	0.01	§	0.01	<0.01	<0.01	<0.01	<0.01
F	0.08	NA	NA	NA	0.08	NA	NA	NA	NA	NA
Fe ₂ O ₃	0.23	1.00	0.80	0.77	0.23	0.66	0.70	0.86	0.50	0.48
I	§	<0.01	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01
K ₂ O	0.50	0.54	0.53	0.53	0.50	0.54	0.54	0.53	0.51	0.53
Li ₂ O*	4.38	3.99	4.13	4.18	4.38	4.26	4.30	4.34	4.35	4.36
MgO	0.99	1.15	0.96	0.99	0.99	0.93	1.00	0.96	0.94	0.89
MnO	§	0.02	0.02	0.02	§	0.03	0.03	0.03	0.04	0.03
Na ₂ O	12.00	13.18	13.37	13.00	12.00	12.39	11.99	12.23	12.33	12.46
NiO	§	0.02	0.01	0.02	§	0.02	0.02	0.01	0.01	0.02
P ₂ O ₅	0.04	0.08	0.07	0.08	0.04	0.08	0.08	0.08	0.09	0.09
PbO	§	<0.01	<0.01	<0.01	§	<0.01	<0.01	<0.01	<0.01	<0.01
SiO ₂	42.44	41.94	42.13	42.09	42.39	42.08	42.12	41.90	42.02	41.89
SnO ₂	§	0.01	0.01	0.01	§	0.01	0.01	<0.01	<0.01	0.01
SO ₃	1.40	1.19	1.20	1.20	1.50	1.25	1.30	1.29	1.31	1.35
TiO ₂	§	0.25	0.22	0.23	§	0.22	0.22	0.23	0.21	0.21
V ₂ O ₅	2.52	2.64	2.64	2.66	2.51	2.74	2.79	2.73	2.76	2.78
ZnO	2.93	3.00	2.88	2.93	2.93	2.99	2.96	2.91	2.93	2.95
ZrO ₂	3.91	3.64	3.53	3.53	3.90	3.67	3.71	3.72	3.67	3.55
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“-“ sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLG9										
Test	G1								G2		
Target SO ₃	0.5%								0.3%		
Glass (kg)	-	391.71	395.25	398.93	402.33	405.63	409.49	412.57	-	415.07	417.95
Constituent	Target	10A-G-9B	10A-G-14A	10A-G-14C	10A-G-15A	10A-G-15C	10A-G-18A	10A-G-18C	Target	10A-G-23A	10A-G-23C
Al ₂ O ₃	6.74	7.80	7.28	6.97	6.87	6.69	6.70	6.51	6.75	6.52	6.47
B ₂ O ₃	8.48	9.19	8.98	8.83	8.73	8.66	8.60	8.57	8.50	8.55	8.54
CaO	2.69	7.44	6.48	5.00	4.29	3.99	3.74	3.54	2.69	3.26	3.29
Cl	0.23	0.07	0.11	0.13	0.14	0.15	0.14	0.14	0.23	0.12	0.14
Cr ₂ O ₃ *	0.59	0.78	0.83	0.84	0.84	0.86	0.83	0.89	0.59	1.25	0.95
Cs ₂ O	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01	<0.01
F	0.09	NA	NA	NA	NA	NA	NA	NA	0.09	NA	NA
Fe ₂ O ₃	0.20	0.44	0.44	0.37	0.34	0.34	0.33	0.32	0.20	0.38	0.36
I	§	0.04	0.05	0.07	0.07	0.08	0.07	0.09	§	0.10	0.11
K ₂ O	5.74	2.15	3.18	4.02	4.39	4.66	4.78	5.13	5.75	5.07	5.35
Li ₂ O*	§	2.90	2.04	1.41	1.00	0.72	0.49	0.36	§	0.28	0.21
MgO	0.95	0.92	0.91	0.99	0.99	0.99	0.93	0.94	0.95	0.97	0.93
MnO	§	0.02	0.02	0.02	0.01	0.01	0.01	0.01	§	<0.01	0.01
Na ₂ O	21.00	14.69	15.36	17.82	19.25	19.52	20.40	19.90	21.00	21.02	19.79
NiO	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.03
P ₂ O ₅	0.14	0.12	0.14	0.15	0.17	0.17	0.18	0.18	0.14	0.17	0.18
PbO	0.01	<0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
SiO ₂	40.76	41.84	41.53	40.94	40.87	40.87	40.55	40.59	40.87	40.13	40.66
SnO ₂	2.83	1.09	1.75	2.26	2.36	2.58	2.66	3.07	2.83	2.85	3.10
SO ₃	0.50	1.02	0.90	0.73	0.67	0.66	0.59	0.58	0.30	0.57	0.47
TiO ₂	§	0.19	0.18	0.16	0.14	0.14	0.13	0.12	§	0.12	0.13
V ₂ O ₅	§	1.95	1.49	0.95	0.66	0.54	0.44	0.34	§	0.26	0.23
ZnO	3.39	3.11	3.41	3.34	3.28	3.32	3.35	3.48	3.40	3.37	3.61
ZrO ₂	5.66	4.23	4.88	4.95	4.90	5.02	5.05	5.21	5.67	4.95	5.44
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRS

“-“ sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLG9									
Test	G2								G3	
Target SO ₃	0.3%								0.2%	
Glass (kg)	-	420.63	422.63	425.93	429.37	432.79	435.57	438.41	-	443.89
Constituent	Target	10A-G-24A	10A-G-24C	10A-G-25A	10A-G-25C	10A-G-29B	10A-G-29D	10A-G-30B	Target	10A-G-33A
Al ₂ O ₃	6.75	6.47	6.39	6.54	6.39	6.28	6.44	6.41	6.76	6.37
B ₂ O ₃	8.50	8.53	8.53	8.52	8.51	8.49	8.49	8.49	8.51	8.50
CaO	2.69	3.16	3.08	2.93	2.86	2.91	2.81	2.84	2.70	2.83
Cl	0.23	0.14	0.13	0.15	0.15	0.17	0.15	0.16	0.23	0.15
Cr ₂ O ₃ *	0.59	0.89	1.05	0.87	1.01	0.91	0.91	1.10	0.59	0.90
Cs ₂ O	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	§	<0.01
F	0.09	NA	NA	NA	NA	NA	NA	NA	0.09	NA
Fe ₂ O ₃	0.20	0.31	0.32	0.30	0.30	0.31	0.30	0.30	0.20	0.30
I	§	0.10	0.12	0.12	0.10	0.11	0.13	0.10	§	0.12
K ₂ O	5.75	5.30	5.39	5.30	5.33	5.48	5.48	5.70	5.76	5.61
Li ₂ O*	§	0.16	0.13	0.09	0.07	0.05	0.04	0.03	§	0.02
MgO	0.95	0.99	0.93	1.00	0.98	0.96	0.93	0.92	0.96	0.91
MnO	§	0.01	<0.01	0.01	0.01	0.01	0.01	<0.01	§	0.01
Na ₂ O	21.00	20.60	20.39	20.71	21.78	20.20	21.14	20.50	21.00	21.10
NiO	0.01	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.01	0.02
P ₂ O ₅	0.14	0.18	0.18	0.19	0.18	0.19	0.18	0.19	0.14	0.18
PbO	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02
SiO ₂	40.87	40.51	40.36	40.81	39.99	39.87	40.12	40.20	40.92	40.15
SnO ₂	2.83	3.08	3.28	3.22	3.10	3.41	3.41	3.49	2.84	3.40
SO ₃	0.30	0.41	0.41	0.37	0.35	0.35	0.33	0.34	0.20	0.30
TiO ₂	§	0.13	0.13	0.12	0.11	0.12	0.12	0.12	§	0.11
V ₂ O ₅	§	0.19	0.16	0.12	0.10	0.08	0.07	0.06	§	0.06
ZnO	3.40	3.51	3.55	3.38	3.41	3.58	3.49	3.57	3.40	3.53
ZrO ₂	5.67	5.29	5.44	5.21	5.21	5.55	5.42	5.44	5.68	5.41
Sum	100.00	100.00	100.00	100.00	100.00	99.04	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“–” sign for empty data field

**Table 4.2. XRF Analyzed Compositions for DM10 Discharged Glass Samples (wt%)
(continued).**

Formulation	ORPLG9							
Test	G3							
Target SO ₃	0.2%							
Glass (kg)	-	446.15	448.97	451.63	454.01	456.41	458.97	462.91
Constituent	Target	10A-G-36A	10A-G-37A	10A-G-38B	10A-G-38D	10A-G-38F	10A-G-39B	10A-G-43B
Al ₂ O ₃	6.76	6.39	6.42	6.41	6.36	6.40	6.44	6.41
B ₂ O ₃	8.51	8.50	8.50	8.51	8.51	8.51	8.51	8.51
CaO	2.70	2.80	2.82	2.76	2.81	2.71	2.73	2.71
Cl	0.23	0.15	0.16	0.16	0.16	0.16	0.16	0.16
Cr ₂ O ₃ *	0.59	1.07	1.04	0.91	0.99	0.87	0.91	0.92
Cs ₂ O	§	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
F	0.09	NA	NA	NA	NA	NA	NA	NA
Fe ₂ O ₃	0.20	0.31	0.31	0.30	0.32	0.29	0.30	0.31
I	§	0.11	0.10	0.09	0.10	0.10	0.10	0.09
K ₂ O	5.76	5.61	5.70	5.61	5.65	5.58	5.65	5.68
Li ₂ O*	§	0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01
MgO	0.96	0.92	0.94	1.01	1.01	1.05	1.04	0.95
MnO	§	<0.01	0.01	0.01	<0.01	0.01	0.01	<0.01
Na ₂ O	21.00	21.38	20.70	21.02	20.84	21.57	21.10	21.48
NiO	0.01	0.03	0.03	0.03	0.03	0.02	0.03	0.03
P ₂ O ₅	0.14	0.18	0.19	0.18	0.19	0.19	0.18	0.18
PbO	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01
SiO ₂	40.92	40.09	40.43	40.48	40.28	40.32	40.29	40.28
SnO ₂	2.84	3.18	3.18	3.19	3.27	3.07	3.21	3.07
SO ₃	0.20	0.30	0.29	0.26	0.26	0.22	0.23	0.21
TiO ₂	§	0.12	0.12	0.11	0.11	0.12	0.12	0.12
V ₂ O ₅	§	0.05	0.04	0.03	0.05	0.03	0.03	0.02
ZnO	3.40	3.45	3.54	3.48	3.52	3.43	3.52	3.48
ZrO ₂	5.68	5.32	5.44	5.42	5.52	5.32	5.45	5.38
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

“-“ sign for empty data field

Table 4.3. Comparison of Discharged Glass XRF Analysis and Target Compositions (wt%).

Formulation	ORPLA20			ORPLD6				
Test	Target	A2		Target	D 3		D5	
Constituent		Y10-G-146C	%Dev.		Z10-G-51D	%Dev.	10A-G-53C	%Dev.
Al ₂ O ₃	6.65	6.72	1.01	10.08	9.26	-8.15	9.61	-4.70
B ₂ O ₃	8.74	8.73*	NC	9.84	9.84*	NC	9.79*	NC
CaO	3.32	3.56	7.24	7.88	7.92	0.43	7.41	-5.99
Cl	0.67	0.53	NC	0.35	0.30	NC	0.24	NC
Cr ₂ O ₃	0.50	0.73	NC	0.50	0.71	NC	0.79	NC
Cs ₂ O	§	<0.01	NC	§	<0.01	NC	<0.01	NC
F	§	NA	NC	0.18	NA	NC	NA	NC
Fe ₂ O ₃	0.19	0.35	NC	0.28	0.33	NC	0.82	NC
I	§	0.10	NC	§	<0.01	NC	0.01	NC
K ₂ O	0.53	0.56	NC	0.17	0.20	NC	0.37	NC
Li ₂ O	§	NA	NC	§	NA	NC	NA	NC
MgO	0.92	0.95	NC	1.00	0.75	NC	0.81	NC
MnO	§	0.01	NC	§	<0.01	NC	0.03	NC
Na ₂ O	24.00	23.09	-3.79	22.00	23.33	6.05	21.94	-0.29
NiO	§	0.09	NC	0.04	0.18	NC	0.05	NC
P ₂ O ₅	§	0.04	NC	0.30	0.37	NC	0.39	NC
PbO	§	0.01	NC	0.01	0.02	NC	0.02	NC
SiO ₂	42.33	42.78	1.05	37.19	36.68	-1.36	37.02	-0.46
SnO ₂	2.74	2.87	4.75	§	0.02	NC	0.13	NC
SO ₃	0.70	0.61	NC	1.30	1.27	NC	1.25	NC
TiO ₂	§	0.05	NC	§	0.19	NC	0.20	NC
V ₂ O ₅	§	0.01	NC	1.96	2.15	10.01	2.16	10.13
ZnO	2.74	2.87	4.75	2.96	2.99	1.04	3.11	5.11
ZrO ₂	5.96	5.35	-10.24	3.98	3.50	-12.03	3.88	-2.45
Sum	100.00	100.00	NC	100.00	100.00	NC	100.00	NC
Sulfate?	-	No	-	-	No	-	Yes	-

* - Target composition calculated based actual proportion of meter feed residues after test

§ - Not a target constituent

NA – Not analyzed

NC – Not calculated

“-“ sign for empty data field

**Table 4.3. Comparison of Discharged Glass XRF Analysis and Target Compositions (wt%)
(continued).**

Formulation	ORPLF7						ORPLG9		
Test	Target	F4		Target	F6		Target	G3	
Constituent		Z10-G-122B	%Dev.		Z10-G-153B	%Dev.		10A-G-43B	%Dev.
Al ₂ O ₃	8.72	8.18	-6.18	8.65	8.37	-3.19	6.76	6.41	-5.25
B ₂ O ₃ *	9.63	9.63	NC	9.56	9.55	NC	8.51	8.51	NC
CaO	9.86	9.95	0.97	9.78	9.66	-1.23	2.70	2.71	0.53
Cl	0.01	0.01	NC	0.01	0.01	NC	0.23	0.16	NC
Cr ₂ O ₃	0.57	0.81	NC	0.56	0.80	NC	0.59	0.92	NC
Cs ₂ O	§	<0.01	NC	§	<0.01	NC	§	<0.01	NC
F	0.08	NA	NC	0.08	NA	NC	0.09	NA	NC
Fe ₂ O ₃	0.23	0.43	NC	0.23	0.48	NC	0.20	0.31	NC
I	§	<0.01	NC	§	<0.01	NC	§	0.09	NC
K ₂ O	0.50	0.53	NC	0.50	0.53	NC	5.76	5.68	-1.32
Li ₂ O	4.41	4.41	NC	4.38	4.36	NC	§	NA	NC
MgO	0.99	1.00	NC	0.99	0.89	NC	0.96	0.95	NC
MnO	§	0.01	NC	§	0.03	NC	§	<0.01	NC
Na ₂ O	12.00	11.74	-2.15	12.00	12.46	3.84	21.00	21.48	2.28
NiO	§	0.01	NC	§	0.02	NC	0.01	0.03	NC
P ₂ O ₅	0.04	0.08	NC	0.04	0.09	NC	0.14	0.18	NC
PbO	§	0.00	NC	§	<0.01	NC	0.01	0.01	NC
SiO ₂	42.73	42.63	-0.26	42.39	41.89	-1.18	40.92	40.28	-1.57
SnO ₂	§	0.01	NC	§	0.01	NC	2.84	3.07	8.29
SO ₃	0.80	0.76	NC	1.50	1.35	NC	0.20	0.21	NC
TiO ₂	§	0.19	NC	§	0.21	NC	§	0.12	NC
V ₂ O ₅	2.53	2.85	12.45	2.51	2.78	10.74	§	0.02	NC
ZnO	2.95	3.03	2.70	2.93	2.95	0.96	3.40	3.48	2.40
ZrO ₂	3.93	3.74	-4.92	3.90	3.55	-9.14	5.68	5.38	-5.22
Sum	100.00	100.00	NC	100.00	100.00	NC	100.00	100.00	NC
Sulfate?	-	No	-	-	No	-	-	Yes	-

* - Target composition calculated based actual proportion of meter feed residues after test

§ - Not a target constituent

NA – Not analyzed

NC – Not calculated

Table 4.4. XRF and DCP Analyzed Compositions for Selected Discharged Glass Samples During DM10 ORP LAW Tests (wt%).

Formulation	ORPLA20					ORPLD6				
Test	A1		A2			Target	D4		D5	
Sample ID	Y10-G-133C		Y10-G-146C				Z10-G-60C		10A-G-53C	
Sample Info.	First Discharge		End of A2				End of D4		End of D5	
Constituent	XRF	DCP	Target	XRF	DCP		XRF	DCP	XRF	DCP
Al ₂ O ₃	8.35	7.18	6.65	6.72	6.20	10.09	8.73	7.94	9.61	9.62
B ₂ O ₃	7.93*	7.93	8.74	8.73**	8.30	9.85	9.85**	9.47	9.79**	10.03
CaO	2.75	3.03	3.32	3.56	3.56	7.89	8.29	6.72	7.41	6.81
Cl	0.31	NA	0.67	0.53	NA	0.35	0.31	NA	0.24	NA
Cr ₂ O ₃	0.42	0.45	0.50	0.73	0.58	0.50	0.85	0.65	0.79	0.63
Cs ₂ O	0.11	NA	§	<0.01	NA	§	<0.01	NA	<0.01	NA
F	NA	NA	§	NA	NA	0.18	NA	NA	NA	NA
Fe ₂ O ₃	3.12	2.20	0.19	0.35	0.32	0.28	0.58	0.55	0.82	1.05
I	0.06	NA	§	0.10	NA	§	<0.01	NA	0.01	NA
K2O	0.52	0.61	0.53	0.56	0.62	0.17	0.22	0.25	0.37	0.46
Li ₂ O	0.13*	0.13	§	<0.01**	0.04	§	<0.01**	0.06	<0.01**	0.06
MgO	1.51	1.43	0.92	0.95	0.98	1.00	0.52	0.61	0.81	0.93
MnO	0.02	0.02	§	0.01	0.01	§	0.01	0.01	0.03	0.03
Na ₂ O	20.65	19.40	24.00	23.09	21.80	22.00	23.17	22.11	21.94	18.70
NiO	0.46	0.34	§	0.09	0.09	0.04	0.24	0.23	0.05	0.07
P ₂ O ₅	0.34	0.36	§	0.04	0.01	0.30	0.39	0.37	0.39	0.37
PbO	<0.01	0.02	§	0.01	0.02	0.01	0.02	0.04	0.02	0.03
SiO ₂	43.68	41.09	42.33	42.78	42.39	37.24	36.80	35.62	37.02	35.51
SnO ₂	1.53	2.09	2.74	2.87	2.87	§	0.02	0.02	0.13	0.14
SO ₃	0.31	NA	0.70	0.61	NA	1.20	1.26	NA	1.25	NA
TiO ₂	0.40	0.29	§	0.05	0.05	§	0.16	0.15	0.20	0.23
V ₂ O ₅	0.42	0.30	§	0.01	0.03	1.96	2.27	2.12	2.16	2.08
ZnO	2.41	2.52	2.74	2.87	2.76	2.96	3.21	2.88	3.11	3.12
ZrO ₂	4.59	4.55	5.96	5.35	4.92	3.98	3.11	2.56	3.88	3.63
Sum	100.00	93.94	100.00	100.00	95.55	100.00	100.00	92.36	100.00	93.50

* - DCP analyzed results

** - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

XRF and DCP Analyzed Compositions for Selected Discharged Glass Samples During DM10 ORP LAW Tests (wt%) (continued).

Formulation	ORPLF7									ORPLG9		
Test	F1		F4			F6			G3			
Sample ID	Z10-G-86A		Z10-G-122B			Z10-G-153B			10A-G-43B			
Sample Info.	First discharge		End of F4			End of F6			End of G3			
Constituent	XRF	DCP	Target	XRF	DCP	Target	XRF	DCP	Target	XRF	DCP	
Al ₂ O ₃	7.12	6.73	8.72	8.18	7.82	8.65	8.37	7.73	6.76	6.41	6.56	
B ₂ O ₃	8.88*	8.88	9.63	9.63**	9.36	9.56	9.55**	9.57	8.51	8.51**	8.15	
CaO	5.10	4.57	9.86	9.95	8.70	9.78	9.66	8.69	2.70	2.71	2.80	
Cl	0.08	NA	0.01	0.01	NA	0.01	0.01	NA	0.23	0.16	NA	
Cr ₂ O ₃ *	0.48	0.37	0.57	0.81	0.65	0.56	0.80	0.66	0.59	0.92	0.71	
Cs ₂ O	0.07	NA	§	<0.01	NA	§	<0.01	NA	§	<0.01	NA	
F	NA	NA	0.08	NA	NA	0.08	NA	NA	0.09	NA	NA	
Fe ₂ O ₃	4.41	3.99	0.23	0.43	0.42	0.23	0.48	0.50	0.20	0.31	0.31	
I	<0.01	NA	§	<0.01	NA	§	<0.01	NA	§	0.09	NA	
K2O	0.45	0.53	0.50	0.53	0.61	0.50	0.53	0.61	5.76	5.68	5.48	
Li ₂ O*	1.79*	1.79	4.41	4.41**	4.47	4.38	4.36**	4.37	§	<0.01**	0.05	
MgO	1.60	1.73	0.99	1.00	1.07	0.99	0.89	0.98	0.96	0.95	1.14	
MnO	0.02	0.02	§	0.01	0.01	§	0.03	0.03	§	<0.01	0.01	
Na ₂ O	16.95	15.17	12.00	11.74	10.30	12.00	12.46	10.53	21.00	21.48	17.86	
NiO	0.21	0.19	§	0.01	0.03	§	0.02	0.03	0.01	0.03	0.03	
P ₂ O ₅	0.07	0.07	0.04	0.08	<0.01	0.04	0.09	<0.01	0.14	0.18	0.20	
PbO	<0.01	0.00	§	<0.01	0.02	§	<0.01	<0.01	0.01	0.01	0.01	
SiO ₂	43.14	41.36	42.73	42.63	41.15	42.39	41.89	40.79	40.92	40.28	38.70	
SnO ₂	0.02	0.03	§	0.01	0.05	§	0.01	0.05	2.84	3.07	3.02	
SO ₃	0.81	NA	0.80	0.76	NA	1.50	1.35	NA	0.20	0.21	NA	
TiO ₂	0.51	0.52	§	0.19	0.20	§	0.21	0.23	§	0.12	0.15	
V ₂ O ₅	1.96	1.81	2.53	2.85	2.60	2.51	2.78	2.57	§	0.02	0.03	
ZnO	3.06	3.19	2.95	3.03	2.78	2.93	2.95	2.84	3.40	3.48	3.45	
ZrO ₂	3.28	3.13	3.93	3.74	3.85	3.90	3.55	3.67	5.68	5.38	5.39	
Sum	100.00	94.08	100.00	100.00	94.09	100.00	100.00	93.85	100.00	100.00	94.05	

* - DCP analyzed results

** - Target values calculated based on simple well-stirred tank model using DCP-AES analyzed boron and lithium concentrations in the first discharged glass sample

§ - Not a target constituent

NA – not analyzed by XRF

Table 4.5. Listing of Dip Samples and Presence of Sulfate Layer During DM10 Melter Tests.

Test	Target (wt.%)			Sampling Date	Sample Name	Sample Location	Secondary Phase Observed
	SO ₃	Cl	Cr ₂ O ₃				
Before A1	0.50	0.67	0.50	10/15/2008	Y10-D-133A	North	No
					Y10-D-133B	East	No
					Y10-D-133C	South	No
End of A1					Y10-D-136A	North	No
					Y10-D-136B	South	No
					Y10-D-136C	East	No
End of A2	0.70	0.67	0.50	10/16/2008	Y10-D-146A	North	No
					Y10-D-146B	East	No
					Y10-D-146C	South	No
End of A3	0.90	0.67	0.50		Y10-D-153A	North	Yes
					Y10-D-153B	East	Yes
					Y10-D-153C	South	Yes
10/17/2008				Y10-D-154A	NA	Yes	
				Y10-D-154B	NA	Yes	
				Y10-D-155A	NA	No	
End of A4	0.80	0.67	0.50	Z10-D-10A	North	Yes	
				Z10-D-10B	East	Yes	
				Z10-D-10C	South	Yes	
				Z10-D-11A	East	Yes	
				Z10-D-11B	NA	No	
End of D1	0.90	0.35	0.35	10/22/2008	Z10-D-35A	North	No
					Z10-D-35B	East	No
					Z10-D-35C	South	No
End of D2	1.10	0.35	0.50	10/23/2008	Z10-D-44A	East	No
					Z10-D-44B	North	No
					Z10-D-44C	South	No
End of D3	1.30	0.35	0.50		Z10-D-53A	North	Yes
					Z10-D-53B	East	Yes
					Z10-D-53C	South	Yes
					Z10-D-53D	South	Yes
					Z10-D-53E	South	No
End of D4	1.20	0.35	0.50	10/24/2008	Z10-D-61A	North	No
					Z10-D-61B	East	No
					Z10-D-61C	South	No
End of D5	1.20	0.35	0.50	1/16/2009	10A-D-57A	North	Yes
					10A-D-57B	East	Yes
					10A-D-57C	South	Yes
Before F1	1.60	0.01	0.56	1/5/2009	Z10-D-84A	South-East	No
					Z10-D-84B	North	No
					Z10-D-84C	South	No
End of F1				1/6/2009	Z10-D-90A	North	No
					Z10-D-90B	East	Yes
					Z10-D-90C	South	No
					Z10-D-90D	East	Yes

NA : Not Applicable

Table 4.5. Listing of Dip Samples and Presence of Sulfate Layer During DM10 Melter Tests (continued).

Test	Target (wt.%)			Sampling Date	Sample Name	Sample Location	Secondary Phase Observed
	SO ₃	Cl	Cr ₂ O ₃				
End of F1	1.60	0.01	0.56	1/6/2009	Z10-D-90E	East	Yes
					Z10-D-91A	East	Yes
					Z10-D-95A	East	No
End of F2	1.40	0.01	0.56	1/7/2009	Z10-D-103A	North	No
					Z10-D-103B	East	Slight
					Z10-D-103C	South	No
					Z10-D-103D	East	No
End of F3	1.20	0.01	0.57	1/7/2009	Z10-D-112A	North	No
					Z10-D-112B	East	No
					Z10-D-112A	South	No
					Z10-D-112D	South	No
End of F4	0.8	0.01	0.57	1/8/2009	Z10-D-123A	North	No
					Z10-D-123B	East	No
					Z10-D-123C	South	No
Before F5	1.4	0.01	0.57	1/12/2009	Z10-D-140A	East	No
End of F5				1/13/2009	Z10-D-143A	North	No
					Z10-D-143B	East	No
					Z10-D-143C	South	No
End of F6	1.5	0.01	0.56	1/13/2009	Z10-D-153A	North	No
					Z10-D-153B	East	No
					Z10-D-153C	South	No
End of G1	0.5	0.23	0.59	1/14/2009	10A-D-19A	North	No
					10A-D-19B	East	Yes
					10A-D-19C	South	No
					10A-D-19D	East	Yes
					10A-D-19F	East	Yes
					10A-D-21A	East	No
End of G2	0.3	0.23	0.59	1/14/2008	10A-D-30A	North	No
					10A-D-30B	East	Yes
					10A-D-30C	South	No
					10A-D-32D	East	No
End of G3	0.2	0.23	0.59	1/15/2009	10A-D-43A	North	Yes
					10A-D-43B	East	Yes
					10A-D-43C	South	Yes
					10A-D-45A	North	No

Table 4.6. Results of PCT Leaching Procedure (ASTM C1285, 7-days at 90°C, Stainless Steel Vessel; S/V=2000m⁻¹) for Crucible Glass and Corresponding Melter Glass Samples from DM10 ORP LAW Tests.

Region		A		D			ANL- LRM-2	WTP Contract Limit
Tank Waste/Sub-Envelope Identification		AN-105/Sub-Envelope A1		AN-102/Sub-Envelope C2				
Sample Type		Crucible Glass	Melter Glass	Crucible Glass	Melter Glasses			
Sample I.D.		ORPLA20	Y10-G-146C	ORPLD6	Z10-G- 60C	10A-G- 53C		
7-Day PCT Concentration in mg/L	B	39.61	35.34	34.64	38.10	29.80	29.08	
	Na	261.40	226.40	219.60	272.30	183.90	165.70	
	Si	91.43	90.87	63.40	76.13	59.73	81.61	
7-Day PCT Normalized Concentrations, g/L	B	1.45	1.30	1.13	1.25	0.98	1.17	
	Na	1.47	1.32	1.35	1.58	1.13	1.12	
	Si	0.46	0.45	0.36	0.44	0.35	0.32	
	pH	11.77	11.58	11.67	11.65	11.45	11.08	
7-Day PCT Normalized Mass Loss (g/m ²)	B	0.72	0.65	0.56	0.62	0.49	0.59	< 2.0
	Na	0.73	0.66	0.67	0.79	0.56	0.56	< 2.0
	Si	0.23	0.23	0.18	0.22	0.17	0.16	< 2.0
7-Day PCT Normalized Loss Rate, g/d/m ²	B	0.10	0.09	0.08	0.09	0.07	0.08	
	Na	0.10	0.09	0.10	0.11	0.08	0.08	
	Si	0.03	0.03	0.03	0.03	0.02	0.02	

Table 4.6. Results of PCT Leaching Procedure (ASTM C1285, 7-days at 90°C, Stainless Steel Vessel; S/V=2000m⁻¹) for Crucible Glass and Corresponding Melter Glass Samples from DM10 ORP LAW Tests (continued).

Region		F			G		ANL-LRM-2	WTP Contract Limit
Tank Waste/Sub-Envelope Identification		AZ-102/Sub-Envelope B2			AP-101/Sub-Envelope A2			
Sample Type		Crucible Glass	Melter Glass		Crucible Glass	Melter Glass		
Sample I.D.		ORPLF7	Z10-G-122B	Z10-G-153B	ORPLG9	10A-G-43B		
7-Day PCT Concentration in mg/L	B	9.78	12.13	12.86	27.42	34.33	29.08	
	Li	12.75	13.27	13.64	NC	NC	NC	
	Na	63.48	51.74	58.12	172.50	248.30	165.70	
	Si	32.28	46.16	41.56	63.57	82.28	81.61	
7-Day PCT Normalized Concentrations, g/L	B	0.33	0.41	0.43	1.02	1.30	1.17	
	Li	0.63	0.65	0.67	NC	NC	NC	
	Na	0.71	0.59	0.63	1.18	1.56	1.12	
	Si	0.16	0.23	0.21	0.32	0.44	0.32	
	pH	11.09	11.12	11.11	11.60	11.78	11.08	
7-Day PCT Normalized Mass Loss (g/m²)	B	0.17	0.20	0.22	0.51	0.65	0.59	< 2.0
	Li	0.32	0.32	0.34	NC	NC	NC	< 2.0
	Na	0.36	0.30	0.31	0.59	0.78	0.56	< 2.0
	Si	0.08	0.12	0.11	0.16	0.22	0.16	< 2.0
7-Day PCT Normalized Loss Rate, g/d/m²	B	0.02	0.03	0.03	0.07	0.09	0.08	
	Li	0.05	0.05	0.05	NC	NC	NC	
	Na	0.05	0.04	0.04	0.08	0.11	0.08	
	Si	0.01	0.02	0.02	0.02	0.03	0.02	

NC – Not calculated

Table 4.7. VHT Results (24 Day) for Crucible Glass and Corresponding Melter Glass Samples that Contain the Maximum Sulfur Concentration Without Formation of Secondary Phases During DM10 ORP LAW Tests.

Region		A		D		F			G	
Tank Waste/Sub-Envelope Identification		AN-105/ Sub-Envelope A1		AN-102/ Sub-Envelope C2		AZ-102/ Sub-Envelope B2			AP101/ Sub-Envelope A2	
Sample Type		Crucible Glass	Melter Glass	Crucible Glass	Melter Glass	Crucible Glass	Melter Glass		Crucible Glass	Melter Glass
Sample I.D.		ORPLA20	Y10-G-146C	ORPLD6	10A-G-53C	ORPLF7	Z10-G-122B (low sulfate)	Z10-G-153B	ORPLG9	10A-G-43B
Based on Layer Thickness	Alteration depth (μm)	75	190	200	300	150 to 300	300	250	450	Coupon fully reacted
	Rate ($\text{g}/\text{m}^2/\text{d}$)	8	21	22	33	17 to 33	33	28	50	
	Compared to limit of 50 $\text{g}/\text{m}^2/\text{d}$	16%	42%	44%	66%	34 to 66%	66%	56%	100%	
Based on Remaining Glass	Alteration depth (μm)	65	140	164	246	164	209	234	370	
	Rate ($\text{g}/\text{m}^2/\text{d}$)	7	15	18	27	18	23	26	41	
	Compared to limit of 50 $\text{g}/\text{m}^2/\text{d}$	14%	30%	36%	54%	36%	46%	52%	82%	

Rates calculated with an average density of $2.65 \text{ g}/\text{cm}^3$

NC – Not calculated

Table 5.1. Maximum Sodium and Sulfur Oxide Concentrations Achieved in Crucible and Melter Tests (wt% in Glass).

Region		A		D		F	G
Tank Waste/	Sub-Envelope Identification	AN-105/ Sub-Envelope A1		AN-102/ Sub-Envelope C2		AZ-102/ Sub-Envelope B2	AP-101 Sub-Envelope A2
Crucible Studies	Na ₂ O	24.0		22.0		12.0	21.0
	K ₂ O	0.5		0.2		0.5	5.76
	SO ₃ (batching)	0.37		0.89		1.44	0.48
	SO ₃ (bubbling)	NM		NM		NM	0.55
Melter Studies	Target Feed Na ₂ O	24.0		22.0		12.0	21.0
	Target Feed SO ₃	0.7		1.2		1.5	< 0.2
	Measured Na ₂ O	23.0		23.2		12.5	21.5
	Measured SO ₃	0.63		1.26		1.35	0.21
Previous Melter Studies	Target Feed Na ₂ O	23.0 [6]	24.0 [7]	20.0 [5]	21.0 [7]	10.0 [6]	
	Target Feed SO ₃	1.0	0.6	1.125	1.1	1.5	
	Measured Na ₂ O	22.0	23.8	19.9	18.1	10.7	
	Measured SO ₃	0.88	0.52	1.07	0.89	1.33	

Table 5.2 Waste Loading Improvements in LAW Glass Formulations Developed for WTP and ORP.

Waste ID	Bechtel Baseline Loadings			Bechtel Correlation (2007)			ORP (2006) Loadings			ORP (2007) Loadings			ORP (2008) Loadings		
AN-105	Glass LAWA44	26.0%	Waste	Glass LAWE4H	27.2%	Waste	Glass LAWA187	30.5%	Waste	Glass ORPLA15	31.6%	Waste	Glass ORPLA20	31.6%	Waste
		20.0%	Na ₂ O		21.3%	Na ₂ O		22.9%	Na ₂ O		24.0%	Na ₂ O		24.0%	Na ₂ O
		0.5%	K ₂ O		0.5%	K ₂ O		0.5%	K ₂ O		0.5%	K ₂ O		0.5%	K ₂ O
		0.2%	SO ₃		0.4%	SO ₃		1.0%	SO ₃		0.6%	SO ₃		0.7%	SO ₃
AP-101	Glass LAWA126	24.5%	Waste	Glass LAWE3	25.4%	Waste	-			-			Glass ORPLG9	29.1%	Waste
		18.5%	Na ₂ O		18.2%	Na ₂ O								21.0%	Na ₂ O
		3.8%	K ₂ O		5.0%	K ₂ O								5.8%	K ₂ O
		0.4%	SO ₃		0.4%	SO ₃								0.2%	SO ₃
AN-107	Glass LAWC22	16.2%	Waste	Glass LAWE5H	20.6%	Waste	-			Glass ORPLB4	26.2%	Waste	-		
		14.4%	Na ₂ O		19.0%	Na ₂ O					24.0%	Na ₂ O			
		0.1%	K ₂ O		0.5%	K ₂ O					0.1%	K ₂ O			
		0.4%	SO ₃		0.5%	SO ₃					0.9%	SO ₃			
AN-104	Glass LAWA137	20.0%	Waste	Glass LAWE6H	20.9%	Waste	-			Glass ORPLC5	31.0%	Waste	-		
		14.6%	Na ₂ O		15.8%	Na ₂ O					23.6%	Na ₂ O			
		0.3%	K ₂ O		0.5%	K ₂ O					0.5%	K ₂ O			
		0.4%	SO ₃		0.5%	SO ₃					0.7%	SO ₃			
AN-102	Glass LAWC35	14.0%	Waste	Glass LAWE7H	16.2%	Waste	Glass LAWC100	24.1%	Waste	Glass ORPLD1	24.9%	Waste	Glass ORPLD6	25.9%	Waste
		12.0%	Na ₂ O		13.5%	Na ₂ O		20.0%	Na ₂ O		21.0%	Na ₂ O		22.0%	Na ₂ O
		0.1%	K ₂ O		0.5%	K ₂ O		0.2%	K ₂ O		0.2%	K ₂ O		0.2%	K ₂ O
		0.6%	SO ₃		0.6%	SO ₃		1.1%	SO ₃		1.1%	SO ₃		1.2%	SO ₃
AZ-101	Glass LAWB83	7.3%	Waste	Glass LAWE9H	11.3%	Waste	-			Glass ORPLE12	19.8%	Waste	-		
		5.5%	Na ₂ O		8.9%	Na ₂ O					16.0%	Na ₂ O			
		0.2%	K ₂ O		0.5%	K ₂ O					0.6%	K ₂ O			
		0.7%	SO ₃		0.7%	SO ₃					1.5%	SO ₃			
AZ-102	Glass LAWB96	3.7%	Waste	Glass LAWE10H	6.2%	Waste	Glass LAWB99	11.9%	Waste	-			Glass ORPLF7	14.3%	Waste
		5.5%	Na ₂ O		5.7%	Na ₂ O		10.0%	Na ₂ O					12.0%	Na ₂ O
		0.1%	K ₂ O		0.5%	K ₂ O		0.4%	K ₂ O					0.5%	K ₂ O
		0.7%	SO ₃		0.8%	SO ₃		1.5%	SO ₃					1.5%	SO ₃

- Empty data field

Figure 2.1. Sulfate solubility determined by remelting with excess SO₃ for forty one new ORP LAW crucible glasses.

Figure 2.2. VHT results for forty one new ORP LAW crucible glasses.
(Percent relative standard deviation (%RSD) of VHT measurement is estimated to be 31 [60])

Figure 2.3. Normalized PCT releases for forty one new ORP LAW crucible glasses.
(Percent relative standard deviations (%RSDs) of PCT measurements estimated from round robin testing are
PCT-B 27, PCT-Na 21, and PCT-Si 15 [66])

Figure 2.4. K-3 corrosion results for thirty eight new ORP LAW crucible glasses and four previous formulations.

Figure 2.5 Rheology of ORLPF feed at 5 Molar sodium; WTP upper bound is also shown.
(The measurements are accurate to $\pm 10\%$)

Figure 2.6. Results of SO_2/O_2 gas bubbling tests on the new ORP LAW glass ORPLG9 at the nominal Cr_2O_3 content of 0.5 wt% and at 1 wt% Cr_2O_3 and the previous ORP Envelope A glasses LAWA161 and LAWA187 at 1150°C. Partial pressure of SO_3 vs. the SO_3 concentration in the glass melt. The horizontal portions indicate the solubility limits while the slopes at lower concentrations provide measures of the activity coefficient of SO_3 in the melt and the onset of a sulfate layer.

(The wt% SO_3 in glass values are accurate to $\pm 10\%$ and the P_{SO_3} values are calculated from gas flow rates accurate to $\pm 5\%$)

Figure 3.1.a. Representative plot of glass pool temperatures during DM10 tests. This plot is from the first test performed (Test A). The temperatures at 2" above the floor, which are most representative of the bulk glass temperature, closely approximate the target of 1150°C. (Temperature measurements are accurate to $\pm 5^{\circ}\text{C}$)

**Figure 3.1.b. Representative plot of glass pool temperatures during DM10 tests. This plot is from the last full test performed (Test G). The temperatures at 2" above the floor, which are most representative of the bulk glass temperature, closely approximate the target of 1150°C.
(Temperature measurements are accurate to $\pm 5^{\circ}\text{C}$)**

Figure 3.2.a. Representative plot of plenum temperatures during DM10 tests. This plot is from the first test performed (Test A). The temperatures fall into the 550 to 350°C range during steady state processing (higher temperatures occurred at the beginning of testing and during sampling periods in between test segments). (Temperature measurements are accurate to $\pm 5^{\circ}\text{C}$)

Figure 3.2.b. Representative plot of plenum temperatures during DM10 tests. This plot is from the last full test performed (Test G). The temperatures fall into the 500 to 350°C range during steady state processing (higher temperatures occurred at the beginning of testing and during sampling periods in between test segments). (Temperature measurements are accurate to $\pm 5^{\circ}\text{C}$)

Figure 3.3.a. XRF analysis of sulfur in DM10 product glasses from Test A.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 3.3.b. XRF analysis of sulfur in DM10 product glasses from Test D. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segments shown.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 3.3.c. XRF analysis of sulfur in DM10 product glasses from Test F. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segments shown.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 3.3.d. XRF analysis of sulfur in DM10 product glasses from Test G.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.1.a. XRF analysis of sodium and silicon in DM10 product glasses from Test A.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.1.b. XRF analysis of sodium and silica in DM10 product glasses from Test D. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.1.c. XRF analysis of sodium and silica in DM10 product glasses from Test F. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.1.d. XRF analysis of sodium and silicon in DM10 product glasses from Test G.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.2.a. XRF analysis of aluminum and calcium in DM10 product glasses from Test A.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.2.b. XRF analysis of aluminum and calcium in DM10 product glasses from Test D. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.2.c. XRF analysis of aluminum and calcium in DM10 product glasses from Test F. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.2.d. XRF analysis of aluminum and calcium in DM10 product glasses from Test G.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.3.a. XRF analysis of zinc and zirconium in DM10 product glasses from Test A.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.3.b. XRF analysis of zinc and zirconium in DM10 product glasses from Test D. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.3.c. XRF analysis of zinc and zirconium in DM10 product glasses from Test F. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.3.d. XRF analysis of zinc and zirconium in DM10 product glasses from Test G.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.4.a. XRF analysis of potassium and magnesium in DM10 product glasses from Test A.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.4.b. XRF analysis of potassium and magnesium in DM10 product glasses from Test D. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.4.c. XRF analysis of potassium and magnesium in DM10 product glasses from Test F. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.4.d. XRF analysis of potassium and magnesium in DM10 product glasses from Test G.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.5.a. XRF analysis of chromium in DM10 product glasses from Test A.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.5.b. XRF analysis of chromium in DM10 product glasses from Test D. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.5.c. XRF analysis of chromium in DM10 product glasses from Test F. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.5.d. XRF analysis of chromium in DM10 product glasses from Test G.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.6.a. XRF analysis of tin in DM10 product glasses from Test A.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.6.b. XRF analysis of tin in DM10 product glasses from Test G.
(See Table 4.2 and Section 4.1 for details of composition analysis)

**Figure 4.7.a. XRF analysis of vanadium in DM10 product glasses from Test D. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown.
(See Table 4.2 and Section 4.1 for details of composition analysis)**

Figure 4.7.b. XRF analysis of vanadium in DM10 product glasses from Test F. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.8.a. XRF analysis of chlorine in DM10 product glasses from Test A.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.8.b. XRF analysis of chlorine in DM10 product glasses from Test D. Note: Other testing and therefore melt pool turnover occurred between the fourth and fifth test segment shown. (See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.8.c. XRF analysis of chlorine in DM10 product glasses from Test G.
(See Table 4.2 and Section 4.1 for details of composition analysis)

Figure 4.9. Secondary sulfur phases on dip sample Z10-D-10C from the end of Test A4.

Figure 4.10. Secondary sulfur phases on dip sample Z10-D-53A from the end of Test D3

Figure 4.11. Secondary sulfur phases on dip sample Z10-D-90E from the end of Test D2.

Figure 4.12. Comparison of PCT results for ORP crucible and melter glasses.
(Percent relative standard deviations (%RSDs) of PCT measurements estimated from round robin testing are
PCT-B 27, PCT-Na 21, and PCT-Si 15 [66])

Figure 4.13 a. SEM image of cross section of crucible glass ORPLA20 after VHT.

Figure 4.13 b. SEM image of cross section of DM10 melter glass Y10-G-146C after VHT.

Figure 4.13. Comparison of VHT coupons for glass formulation ORPLA20.

Figure 4.14 a. SEM image of cross section of crucible glass ORPLD6 after VHT.

Figure 4.14 b. SEM image of cross section of DM10 melter glass 10A-G-53C after VHT.

Figure 4.14. Comparison of VHT coupons for glass formulation ORPLD6.

Figure 4.15 a. SEM image of cross section of crucible glass ORPLF7 after VHT.

Figure 4.15 b. SEM image of cross section of DM10 melter glass Z10-G-153B after VHT.

Figure 4.15. Comparison of VHT coupons for glass formulation ORPLF7.

Figure 4.16 a. SEM image of cross section of crucible glass ORPLG9 after VHT.

Figure 4.16 b. SEM image of cross section of DM10 melter glass 10A-G-53C after VHT.

Figure 4.16. Comparison of VHT coupons for glass formulation ORPLG9.

Figure 4.17. ORP LAW melter glass densities: comparison of glass as-collected from the DM10 melter and after remelting.
(Reported densities are averages of three measurements with percent relative standard deviation (%RSD) of < 0.4)

Figure 5.1. Overview of Na_2O and SO_3 loadings for WTP and ORP glasses.

Figure 5.2 Evolution of Cr_2O_3 content (XRF wt%) in the glasses collected from DM-10 testing.