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PREPARATION AND TESTING OF GLASSES TO SUPPORT VITREOUS STATE LABORATORY DEVELOPMENT OF WTP IHLW FORMULATION ALGORITHM, VSL-06R1240-1, REV. 0

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

P.O. Box 550
Richland, Washington 99352

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Final Report

Preparation and Testing of HLW Glasses to Support Development of WTP IHLW Formulation Algorithm

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for

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Completeness of Testing:

This report describes the results of work and testing specified by the above-listed Test Specifications, Test Plans, and Test Exceptions. The work and any associated testing followed established quality assurance requirements and were conducted as authorized. The descriptions provided in this report are an accurate account of both the conduct of the work and the data collected. Results required by the Test Plans are reported. Also reported are any unusual or anomalous occurrences that are different from the starting hypotheses. The test results and this report have been reviewed and verified.

I.L. Pegg: [signature] **Date:** 12/15/06
VSL Program Director/Principal Investigator

I. Joseph: Innocent Joseph **Date:** 12/15/06
Duratek Sub-Contract Manager

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List of Abbreviations

AES	Atomic Emission Spectroscopy
ANL	Argonne National Laboratory
CCC	Canister Centerline Cooling
CUA	Catholic University of America
DCP	Direct Current Plasma
DOE	United States Department of Energy
DWPF	Defense Waste Processing Facility
EA	Environmental Assessment
EDS	Energy Dispersive X-Ray Spectroscopy
EGCR	Experimental Glass Composition Region
HLW	High Level Waste
IHLW	Immobilized High Level Waste
LAW	Low Activity Waste
LRM	Low Activity Waste Reference Material
NIST	National Institute of Standards and Technology
NQA	Nuclear Quality Assurance
PCT	Product Consistency Test
QARD	Quality Assurance Requirements and Descriptions Document
RPP	River Protection Project
SEM	Scanning Electron Microscopy
$T_{1\%}$	One-Percent Crystal Fraction Temperature
T_L	Liquidus Temperature
TCLP	Toxicity Characteristic Leaching Procedure
VSL	Vitreous State Laboratory
WTP	Hanford Tank Waste Treatment and Immobilization Plant
XRF	X-ray Fluorescence Spectroscopy

SUMMARY OF TESTING

A) Objectives

This report presents results from the High Level Waste (HLW) glass formulation testing performed at the Vitreous State Laboratory (VSL) of the Catholic University of America (CUA) to support the development of an immobilized high-level waste (IHLW) formulation algorithm for the River Protection Project-Hanford Waste Treatment and Immobilization Plant (RPP-WTP). The WTP Project is developing a IHLW formulation algorithm for calculating acceptable HLW glass compositions for the vitrification facility. The preliminary IHLW formulation algorithm (version 3) employs various property-composition models to implement the product quality requirements and key processing constraints on the calculated glass compositions. The primary objective of this work is to assess the acceptability of the glass compositions formulated by the preliminary algorithm. Specifically, this report presents testing results on glasses calculated by the formulation algorithm with respect to Product Consistency Test (PCT), melt viscosity, electrical conductivity, and one-percent crystal fraction temperature ($T_{1\%}$). Completion of the test objectives is addressed in the table below. Since the IHLW formulation algorithm is preliminary in nature and will be revised in the future with updated property-composition models, extremes in compositions and/or properties were preferred in glasses selected for testing in order to explore the boundaries and limitations of applicability of the algorithm.

Test Objective	Objective Met	Discussion
Verify the acceptability of the glass compositions formulated by the *preliminary* glass formulation algorithm and identify potential areas of improvement.	Yes	The WTP Project provided VSL with candidate HLW glasses calculated by the formulation algorithm. Section 2 discusses the selection by VSL of 40 HLW algorithm glasses to be tested. Test data of the selected glasses for PCT, melt viscosity, electrical conductivity, and $T_{1\%}$ are presented in Section 4. The data are compared to established requirements to determine the acceptability of the glass formulations. Due to the preliminary nature of the formulation algorithm and the need to explore the boundaries and limitations of applicability of the algorithm, not all glasses tested were expected to meet the constraint requirements. Potential areas of improvement for subsequent versions of the algorithm are discussed in Section 5.
Develop property-composition models and supporting data that relate IHLW performance on the PCT to IHLW composition and are suitable for predicting the PCT performance of IHLW glasses to be produced in the WTP.	Yes; partially	The PCT data collected on 40 HLW algorithm glasses are presented in Section 4. The IHLW PCT property-composition model will be augmented and refined using these data. The new models will be reported separately.

Develop property-composition models that relate viscosity and electrical conductivity of glass melts to IHLW composition and are suitable for predicting the properties of IHLW glasses to be produced in the WTP.	Yes; partially	Viscosity and electrical conductivity data were collected on 40 HLW algorithm glasses. The data are given in Section 4. The collected data will be used together with data from 152 modeling glasses to support development of the respective models.
Develop models for liquidus temperature (T_L) suitable for predicting the primary liquidus phase in RPP-WTP glasses. This phase is expected to be spinel for AZ-101, AZ-102, and AY-102/C-106 wastes, and thorium-containing phases for AY-101/C-104 wastes.	Yes; partially	As directed by WTP, instead of models used to predict T_L, data were collected to develop models for prediction of $T_{1\%}$ (see Section B below). The collected data, which are described in Section 4, are not only used to determine the acceptability of the HLW algorithm glasses, but will also support future updates of the $T_{1\%}$-property model for spinel (as the principal phase) that was previously developed and reported. Data were collected and $T_{1\%}$ values were estimated for a number of HLW algorithm glasses that precipitated thorium- and zirconium-containing phases. However, models have not yet been developed to predict $T_{1\%}$ when thorium or zirconium phases are the major crystalline phase.

Other objectives in the Test Specification and Test Plans for this work relate to the development of models for other properties. Property-composition models have been developed to predict the Toxicity Characteristic Leaching Procedure (TCLP) performance of IHLW glasses. The TCLP models and associated data are the subjects of a separate report. The scope of testing and data analyses in this report do not include TCLP model development work or assessment of the adequacy of existing TCLP models for the glass compositions described herein, which are intended to support the development and revision of the IHLW formulation algorithm. Section 1 of this report provides more discussion of these test objectives and references to the corresponding reports.

B) Test Exceptions

One of the initial test objectives was to develop models for predicting the liquidus temperature (T_L) of the primary liquidus phase in HLW glasses, which addresses a WTP process requirement to avoid formation and subsequent settling of crystals in the melter. However, in practice, all HLW glasses are in fact produced below the liquidus temperature because of the presence of noble metals in the wastes. In addition, a strict application of the liquidus temperature for phases other than noble metals is overly restrictive on waste loading. In view of these considerations, the WTP has instead adopted an operational definition of the original liquidus temperature requirement: the glass must contain less than 1% by volume of crystalline phases at 950°C. Accordingly, WTP R&T directed the change from modeling T_L to modeling $T_{1\%}$, which was documented in a Test Exception (24590-WTP-TEF-RT-03-078, Rev. 0). The IHLW formulation algorithm also employs a $T_{1\%}$ model to implement the requirement that glass compositions are acceptable with respect to formation of secondary crystalline phases. The current tests followed the same directive and determined $T_{1\%}$ instead of T_L.

C) Results and Performance Against Success Criteria

The data reported in this work were collected on 40 HLW glasses generated by the preliminary IHLW formulation algorithm. The data collected for PCT releases, melt viscosity, electrical conductivity, and estimated $T_{1\%}$ values are important product- and process-related properties of the glasses to be processed at the WTP. Data were collected for each of the 40 glasses and compared to the various requirements driven by product specifications and melter system operations. The comparison was intended to verify the acceptability of the glasses calculated by the formulation algorithm.

The comparison showed that, of the 40 HLW algorithm glasses tested, 20 did not meet one or more of the constraint requirements. This resulted primarily because: (1) constraints were not used in the formulation algorithm to limit the formation of non-spinel (i.e., zirconium- and thorium-containing) phases, (2) the PCT models found in the formulation algorithm under-predicted the PCT releases when the releases were high, (3) the viscosity model over-predicted for some glasses that were close to the lower constraint target of $\eta_{1150} \geq 20$ P, (4) the electrical conductivity model under-predicted for some glasses that were near the upper constraint target of $\varepsilon_{1150} \leq 0.7$ S/cm. A review of the data collected shows that the majority of the glasses that do not meet one or more constraint requirements are either outside the modeling compositional range or crystallize Zr- and Th-containing phases (see Section 4). The IHLW formulation algorithm performed reasonably well for glass compositions that are limited to the ranges used in developing the Phase 1 property-composition models and are limited by iron (instead of zirconium or thorium). It is therefore expected that, with upcoming refinement of the various HLW property-composition models (which will also expand the validity ranges of the models) and their subsequent incorporation into the next version of the IHLW formulation algorithm, the calculated glass compositions should more fully meet the constraint requirements.

The current data show the importance of ensuring that the validity ranges of various models are wide enough to encompass the expected glass compositions. The data also suggest two additional areas for improvement of the IHLW algorithm: (1) a constraint should be included to limit the formation of zirconium- and thorium-phases if some of the current waste projections are found to be realistic, and (2) a constraint that limits the formation of nepheline also needs to be considered to avoid its adverse impact on product quality. Subsequent versions of the IHLW algorithm are expected to take advantage of the testing data to better define the validity and applicability ranges, while future testing of algorithm glasses will be directed towards validation of the algorithm as applied to the anticipated range of WTP glass compositions and properties

D) Quality Requirements

This work was conducted under a quality assurance (QA) program compliant with Nuclear Quality Assurance (NQA)-1 (1989) and NQA-2a (1990) subpart 2.7 and DOE/RW-0333P, Rev. 13, “Quality Assurance Requirements and Description” (QARD). This program is supplemented by a Quality Assurance Project Plan for RPP-WTP work performed at VSL. Test and procedure requirements by which the testing activities are planned and controlled are also defined in this plan. The program is supported by VSL standard operating procedures that were used for this work. Since TCLP testing was not part of the current work scope, requirements found in "Quality Assurance Project Plan for Testing Programs Generating Environmental Regulatory Data," PL-24590-QA00001, (WTP QAPjP) were not applicable.

The following specific areas are subject to QARD: glass preparation, glass compositional analysis, and PCT testing. All work in these areas was performed according to VSL QA programs and implementing procedures that are compliant with QARD.

E) R&T Test Conditions

The WTP Project calculated over 100 glass compositions using the preliminary IHLW formulation algorithm (version 3). These compositions were supplied to VSL, from which 40 glasses were chosen in 4 rounds of selection. The selection was based on considerations of the compositions (i.e., glasses that occupy previously untested compositional regions were selected) and the calculated properties.

The 40 selected glasses were fabricated and characterized with respect to composition, PCT responses, melt viscosity, electrical conductivity, and crystal formation (volume %) vs. heat-treatment temperature. Regression of the volume % crystal fraction data as a function of temperature provided estimates of $T_{1\%}$. All of these data are reported herein and compared with product- and process-related constraint limits.

Crucible melts of the glasses (about 420 g) were prepared by melting mixtures of reagent grade or higher purity chemicals in platinum-gold crucibles at 1150°C for 120 minutes. Mixing of the batched chemicals was accomplished by dry blending, while mixing of the melt was accomplished mechanically using a platinum stirrer. Samples of the resulting glasses were then analyzed by XRF on solid samples.

The PCT (at 90°C for seven days) was performed on the HLW algorithm glasses and the leachates were analyzed by Direct Current Plasma-Atomic Emission Spectroscopy (DCP-AES). The melt viscosities of the glasses were measured, typically in the temperature range of 950 ºC to 1250ºC, using a rotating spindle viscometer, with the viscosity determined from the relation between torque and rotation speed. Electrical conductivity was determined by measuring the impedance of the glass melt as a function of frequency using a calibrated platinum/rhodium probe attached to an impedance analyzer. Measurements were performed over temperature ranges similar to those employed for the viscosity measurements, with the results extrapolated to zero frequency to obtain the direct current conductivity. Both the measured viscosity and electrical conductivity data were fitted to the Vogel-Fulcher equation to give, respectively, interpolated values of viscosity and electrical conductivity at standard temperatures (e.g., 1150ºC). The HLW algorithm glasses were also heat treated isothermally between 650°C and 1200°C (after a pre-melt at 1200°C for 1 hour) at selected temperatures for 70 hours. The heat-treated samples were examined by Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM/EDS) to identify the crystalline phases and to estimate their volume fraction.

Heat treatment with the HLW canister centerline cooling (CCC) temperature profile was performed on 10 of the 40 HLW algorithm glasses. The resulting CCC samples were examined with SEM/EDS and subjected to PCT.

F) Simulant Use

While simulated glasses were prepared for this work, no waste simulants were used. Waste simulants, which are chemical mixtures normally prepared to simulate the physical, chemical, and/or rheological properties of the actual waste, are generally more suited for melter tests than crucible-scale preparation of glasses. All of the simulated glasses in this work were instead prepared from reagent grade chemicals in combinations designed to achieve the target compositions provided to VSL by the WTP Project.

G) Discrepancies and Follow-On Tests

There were no discrepancies. The work reported herein establishes whether or not the glass compositions calculated by the preliminary IHLW formulation algorithm are acceptable for production. Potential areas for improving the preliminary algorithm have been identified. Efforts to improve upon the algorithm will follow before its implementation at the WTP vitrification facility. Additional glasses will be prepared and tested to support the update and improvement of the IHLW formulation algorithm.

SECTION 1
INTRODUCTION

Acceptable glass formulations for vitrification of high-level waste (HLW) waste streams at the Hanford Tank Waste Treatment and Immobilization Plant (WTP) must meet a number of product quality, processability, and waste loading requirements. Glass formulation development and testing has been ongoing at the Vitreous State Laboratory (VSL) to address these requirements, supporting the WTP Project in the diverse areas of melter testing, actual waste testing, and property-composition model development. In general, when the objective was to support melter runs or actual waste testing, glass formulations were designed actively to concentrate on the waste compositions that had been defined or analyzed. This active approach made extensive use of past experience and databases developed at VSL. By contrast, when the objective was to support development of property-composition models, glass formulations were statistically designed after the compositional regions and design constraints had been defined. This approach could provide more even and complete coverage of the compositional regions under study and the data were better suited to property-composition modeling. Regardless of the design approach, however, testing of the glass formulations began with fabrication of the glasses on crucible scale. The prepared glasses were then analyzed for composition before characterization with respect to the various product and processability requirements. In the active-design approach, iterations of this testing process might be necessary if the glass formulated did not meet the various constraints, with the collected data fed back for use in the formulation of the next set of glasses.

Current WTP flow-sheet models and projections predict that the HLW feed compositions delivered to the HLW vitrification facility will change continuously, even though initially only four major waste groups are involved. In addition, the processing schedule will not allow sufficient time to formulate glass compositions using an active-design and testing-based process. Acceptable HLW glass compositions instead will be calculated for each batch of waste transferred to the HLW vitrification facility. The algorithm for calculating these immobilized high-level waste (IHLW) glass compositions is being developed at the WTP [1]. The initial IHLW formulation algorithm employs constraints that are designed to address the various product quality, processability, and waste loading requirements. It also employs preliminary HLW property-composition models developed from previous HLW glass formulation testing to predict various properties of the glasses. Verification and validation of the IHLW formulation algorithm is needed to identify potential deficiencies and areas for possible improvement before its implementation at the WTP.

This report is responsive to the Test Specification [2], Test Plan [3], Test Exception [4], and Test Guidance [5] for HLW property-composition modeling. The principal objective of the work described in these documents is to develop property-composition models to support HLW waste form qualification and processing. A staged approach has been adopted for these tests to allow continual incorporation of evolving information and data on waste compositions and process knowledge. Preliminary models that have been developed are now used in the IHLW formulation algorithm but updates of the preliminary models with additional data have been planned. The current work was intended to not only establish whether or not the glass compositions formulated by the preliminary IHLW formulation algorithm are acceptable for production, but also to identify areas of improvement for future updates of the algorithm.

1.1 Test Objectives

The primary objective of the current work is to verify the acceptability of the glass compositions formulated by the *preliminary* IHLW formulation algorithm and to identify potential areas of improvement for the algorithm [5]. In the course of the present work, the range of applicability of the IHLW formulation algorithm was assessed, and the need for extra constraints to be included in the algorithm was identified. Additionally, the data collected for the HLW algorithm glasses will be used to update and improve the various property-compositions models used in the algorithm. The specific objectives of the HLW glass property-composition modeling work as given in the Test Plan [3] are listed below along with the strategy to address them. The relationship between earlier results and the current work is also discussed below.

- *Develop property-composition models and supporting data that relate IHLW performance on the PCT to IHLW composition and are suitable for predicting the PCT performance of IHLW glasses to be produced in the WTP.*

  Development of the Phase 1 Product Consistency Test (PCT) property-composition models has been reported previously [6]. Data collected from 102 HLW glasses (including replicates) from two statistically designed matrices were used as the basis for model development. Additional PCT data, which have been collected for 75 modeling matrix glasses, will be used in future update of the PCT model [7, 8]. The Phase 1 PCT model is included in the IHLW formulation algorithm to calculate the normalized PCT releases of boron, sodium, and lithium from the HLW glasses. The Waste Acceptance System Requirements Document (WASRD) [9], Rev. 4 requires that HLW glasses have PCT normalized releases of boron, sodium, and lithium lower than the corresponding releases from the Defense Waste Processing Facility-Environmental Assessment (DWPF-EA) glass.

  The collected PCT data from this work will not only be used to verify the performance of the HLW algorithm glasses, but will also be used to update and refine the PCT model.

- *Develop models for liquidus temperature (T_L) suitable for predicting the primary liquidus phase in RPP-WTP glasses. This phase is expected to be spinel for AZ-101, AZ-102, and AY-102/C-106 wastes, and thorium-containing phases for AY-101/C-104 wastes.*

  As directed by the Test Exception [4], instead of liquidus temperature (T_L) models, models to predict one-percent crystal fraction temperatures ($T_{1\%}$) have been developed.

The $T_{1\%}$ results for HLW modeling glasses have been reported previously [6]. The change to modeling $T_{1\%}$ instead of T_L was made because WTP is adopting an operational definition of liquidus temperature and corresponding limit. Specifically, the amount of crystalline phases that are present in equilibrium with the glass melt at 950°C must be less than 1 volume %. This is a less conservative operational definition and is adopted in recognition of the fact that all HLW glasses are, in actuality, produced below the liquidus temperature of the glass melt as a result of the presence of sparingly soluble species such as noble metals in the wastes. A strict application of the liquidus temperature criterion (for phases other than noble metals) is also overly restrictive on waste loading. Accordingly, the IHLW formulation algorithm employs the processing requirement of $T_{1\%}$ (plus uncertainty) ≤ 950°C.

The difference in compositions between (i) AZ-101, AZ-102, and AY-102/C-106 wastes and (ii) AY-101/C-104 wastes was addressed in Phase 1 by the development of two different experimental glass composition regions (EGCRs), each focusing on the expected characteristic compositions of the two groups [6]. Preliminary $T_{1\%}$ models suitable for predicting spinel as the primary crystalline phase have been developed and reported [6, 7]. The recommended spinel model has been adopted in the IHLW formulation algorithm to calculate $T_{1\%}$ and to avoid glasses that do not meet the processing limit. Similar $T_{1\%}$ models for predicting non-spinel (i.e., zirconium- and thorium-containing) phases have not been developed, partly because of a relative lack of data. The current IHLW formulation algorithm therefore does not constrain $T_{1\%}$ for secondary phases other than spinel.

As with the case of PCT, the collected $T_{1\%}$ data from this work will not only be used to verify the processability of the HLW algorithm glasses, but will also be used to update and refine the $T_{1\%}$ model.

- *Develop property-composition models and supporting data that relate IHLW performance in the TCLP to IHLW composition and are suitable for predicting the TCLP performance of IHLW glasses to be produced in the WTP.*

Toxicity Characteristic Leaching Procedure (TCLP) data have been collected on 118 HLW glasses (including replicates and spiked glasses) and the data were used to support the development of a TCLP cadmium release model. The data and the model have been reported previously [10]. The recommended TCLP cadmium-release model has been used in the IHLW formulation algorithm to calculate the TCLP release of cadmium from HLW glasses. The current testing, however, did not include TCLP. The WTP Poject has elected to defer further TCLP testing and corresponding related updates to the IHLW algorithm because it is not cost effective at this time. Current data indicate that TCLP is one of the least restrictive constraints; thus, a graded approach to IHLW algorithm development is being implemented for TCLP testing. Once the acceptable compositional range has been adequately defined by other constraints (e.g., $T_{1\%}$, PCT, conductivity, etc.), additional testing for TCLP response can be initiated as needed. Such testing, and a corresponding revision of the TCLP cadmium release model and IHLW algorithm, will be required if the WTP processes feeds outside of the composition ranges described by the current version of the TCLP model and IHLW algorithm. (Archived samples of the algorithm glasses will be available for future TCLP testing, if so directed by the Project.)

- *Develop property-composition models that relate viscosity and electrical conductivity of glass melts to IHLW composition and are suitable for predicting the properties of IHLW glasses to be produced in the WTP.*

  Viscosity and electrical conductivity data have been collected on 102 HLW glasses (including replicates) and part of the data (60 glasses) were used in the investigation of model forms and development of viscosity and conductivity models. These data and models have been reported previously [11]. Viscosity and conductivity data for 50 additional glasses have been collected during the Phase 2HLW matrix glass testing [8]. The initial viscosity and electrical conductivity models are used in the IHLW formulation algorithm to ensure that the glass melt will meet the processing requirements of the melter system.

  As with the other data collected, the viscosity and electrical conductivity data measured for the HLW algorithm glasses will be used to establish their acceptability as well as to improve and refine the HLW viscosity and electrical conductivity models.

- *Develop property-composition models that relate density of IHLW glasses to composition in order to predict overall volumes of IHLW that would be produced from a given waste feed.*

  The density property-composition model may be developed and reported at a later date if so directed by WTP R&T.

1.2 Test Overview

The WTP Project calculated target glass compositions for a series of example waste compositions using the preliminary IHLW formulation algorithm. The waste compositions originated from various sources (see Section 2). The resulting HLW algorithm glass compositions were then provided to VSL, where a total of 40 glasses were selected in 4 stages for testing. The compositions of the selected glasses and the rationale for their selection were transmitted to WTP for information before glass preparation and testing began.

Each of the HLW algorithm glasses selected was fabricated with laboratory chemicals on crucible scale. The prepared glasses were tested for (i) product consistency test (PCT) response, (ii) viscosity and electrical conductivity as functions of temperature, and (iii) crystal type and fraction at equilibrium as functions of temperature. The data collected from (iii) were used to estimate $T_{1\%}$ for each glass. The measured data were compared to the calculated values and used to determine whether the glasses met all product quality and processability requirements. After completion of testing, 10 glasses were selected from the original set of 40 glasses for canister centerline cooling (CCC) heat treatment. The CCC glass samples were characterized with respect to secondary phase formation and PCT responses.

The selection of HLW algorithm glasses to be tested is discussed in Section 2. The experimental procedures used in testing the glasses are described in Section 3. Section 4 presents the data collected.

SECTION 2
SELECTION OF HLW ALGORITHM GLASSES

The IHLW formulation algorithm is being developed for use at the WTP for batching HLW and glass-forming chemicals (GFCs) to produce HLW glass compositions that meet all product quality requirements and key processing constraints. In cases where multiple glass compositions can meet all constraints, the composition is optimized to increase the robustness of the process and to lower the risk of processing difficulties (e.g., it is advantageous to process some distance from, rather than too close to, any one property limit). The formulation algorithm also incorporates process measurement and property prediction uncertainties. In generating glasses for the present testing, the IHLW algorithm was extended beyond the ranges of validity of the property-composition models that it employs in order to explore the boundaries and limitations of its applicability,

A detailed description of the IHLW formulation algorithm can be found in Reference [1]. This section briefly summarizes the algorithm constraints that are important to the present glass testing and the waste bases that were used in calculating the HLW algorithm glasses (Section 2.1). It also discusses the selection of the 40 HLW algorithm glasses that were tested (Section 2.2).

2.1 HLW Algorithm Glass Calculations

The primary inputs for the IHLW formulation algorithm are compositions of the blended HLW and the individual GFCs. The algorithm calculates the following outputs: (i) the volume of HLW to be transferred to the melter feed preparation vessel (MFPV), (ii) the mass of each GFC to be added to the MFPV batch, (iii) the composition of the glass to be produced, and (iv) the predicted properties of the resulting IHLW glass with associated uncertainties. The IHLW formulation algorithm employs three sets of constraints in the calculation:

- Hard Constraint. These constraints must be met by all glass compositions for a formulation to be accepted. The hard constraints are key product and processing related property limits for a processable and compliant glass to be produced. Since the glass properties are estimated using HLW property-composition models, with appropriate uncertainties incorporated, the hard constraints also include single glass component concentration constraints to ensure that the glasses produced will be within the compositional ranges within which the models were developed. The IHLW formulation algorithm hard constraints, as provided by the WTP Project, are reproduced in Tables 2.1 and 2.2. Note that there are overlaps for the two constraints listed each for viscosity and electrical conductivity in Table 2.1, which may involve some redundancy. For example, the upper constraint for electrical conductivity at 1100°C is met automatically if the upper constraint for the same property at 1200°C is met. This affects the way in which the uncertainties are included in the constraints. The glass component limits in Table 2.2 are mostly identical to those found for glasses used to develop Phase 1 HLW property-composition models, with the major exception being Al_2O_3 and Na_2O. The upper limits for Al_2O_3 and Na_2O in glasses used to develop Phase 1 models were, respectively, 8.5 wt% and 15 wt% [6, 11]. In contrast, the algorithm glasses tested range up to 13 wt% of Al_2O_3 and 20 wt% of Na_2O. This was designed, as stated above, to explore the boundaries and limitations of the IHLW formulation algorithm applicability.

- Firm Constraint. There is one "firm" constraint of waste loading, which is defined by the WTP Contract (Table T.S-1.1) [12]. The constraint is met by obtaining the waste fraction of at least one component (or group of components) in glass at the level listed in the table. In other words, the waste loading factor (defined as maximum mass ratio of glass component (or group of components) to the waste loading limit in Table TS-1.1) needs to be ≥ 1 to meet the constraint. Table 2.3 lists the firm constraint of waste loading. If this constraint is met with a glass composition that meets all the hard constraints, then it will be met. Otherwise, if no composition can be found to simultaneously meet all the hard constraints and waste loading constraint, then waste loading will be lowered (below the constraint) to produce a glass with the highest possible waste loading while meeting all the hard constraints.

- Soft Constraint. For many waste compositions, the hard and firm constraints can be met with additional degrees of freedom left in the glass composition. These degrees of freedom are used to meet WTP operations goals such as increasing waste loading above the minimum limits, moving the glass composition closer to those previously tested in pilot scale melters, improving product durability beyond the required values, and moving away from various constraints to increase the "robustness" of the glass composition. To implement the soft constraints, target component concentrations, property values, and waste loading are set along with weighting factors. A penalty is assigned to a given soft constraint depending on the distance from the target and the weight factor. The algorithm seeks to minimize the summed penalties. Table 2.4 provides an example set of soft constraints used in the IHLW formulation algorithm, which is the same set of constraints that was used in the calculation of the glass compositions used in this work. These constraints can be changed to address changing project priorities.

The formulation algorithm seeks to calculate a glass composition that meets all the above constraints by varying the relative concentrations of the HLW and the GFCs in the MFPV. Compositions of the GFCs are given in Table 2.5.

In formulating target glass compositions for the current tests, the IHLW formulation algorithm made use of a series of example waste compositions. The waste compositions came from the following sources:

- The WTP dynamic flow-sheet model (G2) output data from runs 3.1vv [13], 3.1.1a [14], 4.0.3.b [15], and 4.0.8a [16]. For the version 3 runs, chemical snapshots from the HLW Concentrate Receipt Vessel batch composition data were used. For the version 4 runs, chemical snapshots from the MFPV batch composition data were used, with the GFC contribution in the MFPV heels subtracted. The G2 runs were pre-screened for these calculations by limiting the batches considered to those that resulted from one of the four WTP Research and Technology tanks (AZ-101, AZ-102, AY-102/C-106, and AY-101/C-104). Multiple batches of roughly the same composition were also removed. For consecutive batches with slowly varying compositions, only the extreme and/or endpoint compositions were used.

- Characterization data from actual tank waste samples that were pretreated and blended with various prototypic process additions and recycles were used. Five compositions were used: one for AZ-101 [17], one for AZ-102 [18], and three for AY-102/C-106 [19].

- An average G2 composition was calculated. For each of the four G2 runs considered, a weighted average composition of all batches for the four tanks being considered was taken. A numerical average was then determined for the four weighted average compositions. This average composition was used by itself and also as a basis for manually adjusted waste compositions discussed below.

- Waste compositions from above provide good estimates of the currently expected HLW feed compositions. They resulted in glass compositions relatively close to those found in earlier HLW glass testing. Few of these glass compositions were expected to give surprising results when fabricated and tested. Another set of compositions was therefore manually developed to challenge the boundaries of what may be formulated when the wastes delivered would be sufficiently far from current expectations. The average composition discussed above was used as the starting point in generating the made-up wastes. With the exception of CaO, those components that made up more than 1 wt% of the average composition were selected together with CdO and Cr_2O_3 as major components. The sum of all minor components was 7.02 wt% and was held constant, while the concentrations of the 12 major components were varied in relative proportions. Each of these wastes was developed to challenge the algorithm to formulate an acceptable glass. It should be noted that these wastes were not systematically varied to cover the entire possible waste composition region. However, an attempt was made to cover as effectively as possible the composition “types” that are likely to be problematic.

Over 100 HLW algorithm glasses were calculated using the constraints and waste compositions described above (version 3 of the preliminary algorithm was used in the calculation). The constraints and waste compositions were varied to purposely generate extreme glass compositions for use in defining the range of algorithm applicability. The calculated glass compositions were supplied in several stages by the WTP Project to VSL, where a total of 40 glasses were selected for testing. The selected glasses are discussed in Section 2.2.

2.2 HLW Algorithm Glass Selection

To support development and verification of the IHLW formulation algorithm, VSL selected 40 glasses for testing from the algorithm calculation results provided by the WTP Project. The selection was made in several rounds, with the results obtained used as feedback in subsequent rounds. Table 2.6 lists the 40 HLW algorithm glasses that were selected, with their corresponding algorithm identifications and highlights in compositions and calculated properties. Table 2.7 summarizes for each selected glass, the waste composition basis, the melter feed mix, and the calculated glass properties.

The first round of selection yielded 8 glasses (HLW-ALG-01 through -08), all of which were based on "made-up" wastes. This was because, as discussed above, the vast majority of the algorithm glasses calculated for the wastes from flow-sheet model results are relatively similar in composition to those found in earlier HLW glass and melter testing. In general, the wastes from G2 model runs are high in Fe_2O_3 while the glasses are limited by Fe_2O_3, (Al_2O_3+Fe_2O_3+ZrO_2) or ThO_2. Testing of these model-based glasses was not expected to give results much different than from previous testing. The "made-up" wastes, by contrast, are compositionally more extreme; for example, HLW-ALG-04 was formulated for a waste with 83.08 wt% Fe_2O_3, 6.60 wt% of NiO and 3.3 wt% Cr_2O_3. Another example (HLW-ALG-05) shows high concentrations of SrO (27.50 wt%) and MnO (19.20 wt%). High concentrations of ZrO_2 and ThO_2 are also found in some of these "made-up" wastes (e.g., HLW-ALG-07). As a result, the selected glasses occupy rather different compositional regions compared to those from earlier testing: HLW-ALG-07, for example, meets the TS-1.1 requirement by incorporating more than 14 wt% of (Al_2O_3+ZrO_2), a component limit that has not been invoked in previous testing. Some of the made-up waste glasses simultaneously meet more than one of the TS-1.1 constraints (e.g., HLW-ALG-18 meets the TS-1.1 loading requirements for Al_2O_3 and Al_2O_3+Fe_2O_3+ZrO_2).

In addition to glass compositions, calculated properties also helped guide the selection. In particular, glasses with high predicted viscosity (> 55 P at 1150ºC) were of interest since relatively few data in this region were available for the development of the property-composition model used in the algorithm. For the same reason, glasses with high predicted PCT releases were chosen (e.g., the predicted normalized PCT B release for HLW-ALG-03 was 5.029 g/l). Finally, the predicted $T_{1\%}$ values (plus uncertainty) of the selected glasses covered a wide range from 721.2ºC up to the constraint limit of 950.0ºC.

The second round of selection involved some new candidate glasses and resulted in 15 glasses (HLW-ALG-09 through -23). Additional algorithm calculations supplied the new candidate glasses, many of which were formulated with a new constraint to limit the total alkali concentration (i.e., (Na_2O+2*Li_2O+0.66*K_2O) ≤ 21.5 wt%). It should be noted that the new constraint was implemented only for the purpose of generating HLW glasses for testing and *not* intended as a new compositional constraint in the IHLW formulation algorithm. This new constraint was adopted to reflect concerns with respect to increased melter refractory corrosion at these high alkali contents. Glasses with high alkali concentrations from the first round were found in preliminary testing to result in little formation of secondary phases after heat treatment. Since the high alkali contents were generally driven by the $T_{1\%}$ constraint, it was decided to artificially limit the total alkalis. Many of the selected glasses therefore contain ≤ 21.5 wt% of total alkalis. Additionally, to investigate the effects of varying the alkali concentrations, the glass selection included series of glasses that were based on the same waste composition, but with different alkali concentrations. For example, HLW-ALG-19 and -20 were formulated for the same waste composition as for HLW-ALG-03, but with reduced total alkali concentration (25.1 wt% in HLW-ALG-03, 23.3 wt% and 21.5 wt% in -20 and -19, respectively). Another series of glasses with a similar design of gradually lowered alkali concentrations included HLW-ALG-21, -22 and -23. The selection process otherwise followed closely that used in the first round in that unusual composition combinations were chosen, while emphasis was also placed on calculated properties in regions where there was a relative deficiency of data during earlier HLW modeling studies. Among the compositional highlights in the selected glasses are high ThO_2 (6.01 wt%) and low Fe_2O_3 (1.93 wt%) in HLW-ALG-11 (Fe_2O_3 was in fact added as a GFC). Relatively high concentrations of ZrO_2 (9.19 wt%), ThO_2 (5.51 wt%), and UO_3 (6.13 wt%) were simultaneously found in HLW-ALG-13.

A total of 7 glasses were selected during the third round (HLW-ALG-24 through -30). The selected glasses included a Cr_2O_3-limited glass with low (Al_2O_3+Fe_2O_3+ZrO_2) content (13.90 wt% in HLW-ALG-25). For comparison, HLW-ALG-29 was chosen for an unusually high concentration of (Al_2O_3+Fe_2O_3+ZrO_2), at 26.89 wt%. The glass HLW-ALG-30 was formulated for the actual waste found in AZ-101.

New algorithm calculations were performed for the last round of glass selection. The new calculations were performed with modified constraints and waste compositions from the dynamic flow-sheet modeling (G2) runs. The constraints were modified because preliminary testing results for glasses from earlier rounds showed that the viscosity data were often below the constraint limit of $\eta_{1150} \geq 20$ P and that the $T_{1\%}$ constraint might be overly restrictive. It should again be noted that the new constraints were implemented only for the purpose of generating candidate glasses for testing and were not meant to replace the constraints discussed in Section 2.1. The constraint modifications included:

- Increase of the $T_{1\%}$ limit by 125ºC to 1075ºC;
- Setting the weight on the $T_{1\%}$ soft constraint to 0;
- Setting the weight on waste loading soft constraint to 1000, which effectively forced the waste loading to the maximum value.

The final set of HLW glasses selected (HLW-ALG-31 through -40) primarily consisted of glasses calculated using the modified constraints so that they could be compared with glasses that were formulated with different constraints for the same waste bases from earlier rounds. Since the $T_{1\%}$ constraint was relaxed, the waste loadings of the selected glasses were considerably higher than those formulated for the same wastes found in earlier rounds. For example, the waste loading for HLW-ALG-40, which was formulated for the actual AZ-101 waste, is 39.53%, compared with 31.09% for HLW-ALG-30, which was also formulated for the same waste composition.

Table 2.8 lists the target compositions of the 40 HLW algorithm glasses selected. Note, however, that the compositions of the HLW algorithm glasses provided by the WTP comprised up to 63 component oxides, many of which were uncommon and present only at very low concentrations (e.g., Pa_2O_5 at << 0.01 wt%). In order to keep the number of components manageable and to avoid handling of extremely radioactive materials, oxides that were present at less than 0.025 wt% were omitted from the WTP formulations. The radioactive thorium oxide and uranium oxide were retained in the formulations if their concentrations were above 0.025 wt%. The contributions of the omitted oxides were generally very small (< 0.25 wt% total). The compositions were then re-normalized to 100 wt% after dropping the very minor oxides before glass preparation. The target compositions listed in Table 2.8 are therefore slightly different than those provided by the WTP Project. The slight changes in compositions are not expected to impact the measured glass properties (for example, the estimated uncertainties associated with measurements of electrical conductivity are ± 20%, which is larger than the expected effect of the < 0.25 wt% of oxides omitted).

SECTION 3
EXPERIMENTAL PROCEDURES

After the selection of HLW algorithm glass compositions, the glasses were fabricated at VSL on a crucible scale (about 420 grams). The resulting glass products were sub-divided into portions that were used for the various tests, including PCT, measurements of viscosity and electrical conductivity, and $T_{1\%}$ determination. The experimental procedures employed in preparing and characterizing the 40 HLW algorithm glasses are summarized in this section.

3.1 Glass Batching and Preparation

All selected HLW algorithm glasses were fabricated at VSL using reagent grade chemicals. The Technical Procedure *Crucible Melts* [20] describes the details of crucible preparation of HLW glasses. The following briefly summarizes the procedural steps.

Glass preparation began with a batching sheet that provided information on the required starting materials. The information included the chemicals needed, identification of the chemicals according to the vendors and catalog numbers, the associated purity, together with the amount required to produce a given amount of glass. Chemicals were weighed and batched according to the batching sheets.

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

3.2 Analyses of Glass Composition

Compositions of the HLW glasses were analyzed using x-ray fluorescence spectroscopy (XRF). Powdered glass samples (−200 mesh) were analyzed with an ARL 9400 wavelength dispersive XRF spectrometer, which was calibrated over a range of glass compositions using standard reference materials traceable to the National Institute of Standards and Technology (NIST), as well as waste glasses including the Argonne National Laboratory – Low Activity Waste Reference Material (ANL-LRM), the Defense Waste Processing Facility – Environmental Assessment (DWPF-EA) glass, and WTP HLW and LAW glasses.

3.3 Viscosity

The viscosity of the glass melt, η, was measured using a Brookfield viscometer and the Technical Procedure *Glass Viscosity and Conductivity* [21]. The viscosity was determined from the relation between torque and rotation speed. Measurements were normally performed in the temperature range of 950ºC to 1250ºC and the data were interpolated to standard temperatures using the Vogel-Fulcher equation:

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

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

3.4 Electrical Conductivity

The electrical conductivity, σ, was determined, according to the VSL Technical Procedure *Glass Viscosity and Conductivity* [21], by measuring the impedance of the glass melt as a function of frequency using a calibrated platinum/rhodium probe attached to a Hewlett-Packard model 4194A impedance analyzer. Measurements were performed over temperature ranges similar to those employed for the viscosity measurements (950ºC to 1250ºC). The results were extrapolated to zero frequency to obtain the direct current conductivity. The measured data were then interpolated to standard temperatures using the Vogel-Fulcher equation:

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

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

3.5 Product Consistency Test

The PCT data for the HLW algorithm glasses were collected at VSL from tests performed at 90°C for 7 days according to ASTM C1285 [22], as required in Specification 1 of the WTP contract [12]. Samples of crushed glasses (4 g, 100-200 mesh or 75-149 μm) were placed in 40 ml of test solution (de-ionized water) inside 304L stainless steel vessels. All tests were conducted in triplicate, and in parallel with the DWPF-EA standard glass included in each test set. The leachates were sampled after 7 days, when 1 ml of sampled leachate was mixed with 20 ml of 1M HNO_3 and the resulting solution analyzed by direct current plasma atomic emission spectroscopy (DCP-AES). Another 3 ml of the sampled leachate was used for pH measurement.

In addition to the leachate concentrations themselves, it is convenient and conventional to also consider the *normalized* leachate concentrations. The normalization is performed by dividing the concentration measured in the leachate for any given component by its fraction in the glass. Target mass fractions in glass are used in this work. Thus, the *normalized* concentration r_i of element i is calculated from the elemental concentration c_i measured in the leachate (in ppm) as:

$$r_i = \frac{c_i}{f_i} \,, \tag{3.5.1}$$

where f_i is the *target* mass fraction of element i in the glass (i = B, Li, Na, and Si). The normalized mass loss is then obtained from:

$$L_i = \frac{r_i}{(S/V)} \,, \tag{3.5.2}$$

where S/V is the ratio of the glass surface area to the volume of the leachant, which for the standard PCT is 2000 m^{-1}. Assuming this value of S/V, if r_i is expressed in g/l, one need only divide by two to obtain L_i in g/m^2 (because 1 g/l = 1000 g/m^3). Finally, the 7-day normalized PCT leach rate can be calculated as the normalized mass loss per day (i.e., normalized leach rate in $g/(m^2\text{-day}) = L_i/7$). This report presents the PCT results in leachate concentration (ppm) and normalized leachate concentration (g/l).

Specification 1 of the WTP contract requires that the normalized mass losses of B, Na, and Li in PCT be below the respective values for the DWPF-EA glass. The nominal values for normalized leachate concentrations from the DWPF-EA glass are 16.695, 13.346, and 9.565 g/l for B, Na, and Li, respectively [9]. The corresponding value for Si is 3.922 g/l.

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

Glass samples (about 5 grams each) were heat-treated in platinum, platinum-gold, or platinum-rhodium crucibles (5 ml) at a pre-melt temperature of 1200°C for 1 hour, followed by heat treatment for 70 hours at prescribed temperatures between 650°C and 1200°C. At the end of the heat-treatment period, the glass samples were quenched by contacting the crucible with cold water. This quenching freezes in the phase assemblage in equilibrium with the melt at the heat-treatment temperature. The sample was then prepared for Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy (SEM/EDS) examination by grinding and sieving (−18 mesh). The microscopic and spectroscopic examinations (Model JSM-5910LV, equipped with Oxford Instruments INCAEnergy 300 system) were used to determine the volume fraction of crystalline phases and identify the dominant crystalline phases. For each glass, heat treatments were performed to obtain non-zero vol% data for at least three temperatures in order to reasonably constrain the $T_{1\%}$ value. Efforts were also made to bracket the $T_{1\%}$ temperature so that it could be obtained by interpolation rather than extrapolation.

The crystalline phases found in the heat-treated glasses were characterized by SEM/EDS and the volume percents were obtained as the average of 4 to 10 viewing area counts from glass sub-samples collected at different locations in the crucible (e.g., near the bottom, center, side of the crucible, etc.). The selection of the glass fragments and viewing areas was intended to provide a representative measure of the overall crystal fraction in the sample.

The $T_{1\%}$ value for each glass was obtained by linear regression of the heat-treatment temperature (°C) as the dependent variable versus crystal fraction (vol%) as the independent variable. The choice of vol% (which has the larger measurement error) as the independent variable, rather than the temperature (which has the smaller measurement error), is contrary to the selection that would normally be made for regression. However, as discussed in a previous $T_{1\%}$ modeling report [6], there are significant advantages to using this "inverse regression" approach in the present application. The differences in the $T_{1\%}$ values estimated using either choice of independent variable were small.

3.7 Canister Centerline Cooling

Selected HLW algorithm glasses underwent canister centerline cooling (CCC) heat treatment before additional testing was performed. Samples that underwent CCC were distinguished from the original glass samples by adding the extension "CCC" to the sample IDs (e.g., HLW-ALG-08CCC is the sample resulting from CCC treatment of HLW-ALG-08). The CCC temperature profile was provided by the WTP Project [23] (see Table 3.1 and Figure 3.1). As in the case of isothermal heat-treatment, the glass samples (about 80 g) in platinum crucibles were maintained at a pre-melt temperature of 1200°C for 1 hour before initiation of the CCC treatment. The samples recovered after CCC treatment were subjected to PCT and SEM/EDS examination.

SECTION 4
RESULTS AND DISCUSSION

This section presents the characterization and test data of the selected HLW algorithm glasses. Chemical compositions of the glasses, determined by XRF analyses, are presented in Section 4.1. The Product Consistency Test (PCT) data are discussed in Section 4.2. Section 4.3 summarizes the viscosity and electrical conductivity data. Section 4.4 summarizes the heat-treatment data for the 40 HLW algorithm glasses. Section 4.4 also presents the one-percent crystal fraction temperature ($T_{1\%}$) results, which were estimated by regression of the heat-treatment data. The results of CCC heat treatment of selected glasses are provided in Section 4.5.

4.1 Chemical Composition

Results of compositional analysis by XRF of the HLW algorithm glasses are given in Table 4.1. Note, however, that the batched (target) compositions are used below for calculating normalized PCT responses since they are derived from simple weighings of pure chemicals, which are believed to provide the best compositional data; previous work followed the same approach [6]. Since target glass compositions are used in modeling, the principal role of the composition analysis is one of confirmation.

The analyzed compositions for the major components generally show good agreement with the targets. The primary exception is Al_2O_3 when the concentration is *low* (< 5 wt%), with the analyzed values for Al_2O_3 in those cases generally higher than the targets. This is believed to be due to a relative lack of XRF calibration data in this region. Alternative analyses of selected samples by direct current plasma-atomic emission spectrometry yielded results that are in better agreement with the targets. For selected minor components, especially barium and magnesium, discrepancies are also evident. For example, analysis of HLW showed no presence of BaO in selected glasses, even though the target values in these glasses were as high as 0.1 wt% (e.g., see the target and analyzed BaO values for HLW-ALG-24). The "non-detect" for barium was traced to spectral interferences from other components, chiefly strontium in this case. Thus while the presence of barium *was* actually detected, the analytical software reported that as insignificant because of the high background due to strontium. In some cases, interferences from Ce_2O_3 also appeared to result in "non-detect" of La_2O_3 and TiO_2.

4.2 Product Consistency Test (PCT) Results

The data for PCT releases of boron, lithium, sodium, and silicon for the 40 HLW algorithm glasses are listed in Table 4.2. The PCT results are presented as raw leachate concentrations (in ppm) and normalized leachate concentrations (in g/l). Normalized PCT releases were calculated using target mass fractions in glass. Figures 4.1 through 4.3 show, respectively, the measured PCT boron, lithium, and sodium releases for the 40 glasses with the predicted releases (plus uncertainties). Table 4.3 summarizes the measured values of the various properties, with those that do not meet the hard property constraints highlighted in boldface. Glasses that were outside the compositional range of HLW glasses used to develop Phase 1 models, are also highlighted.

It is seen in Table 4.3 that all algorithm glasses except one (HLW-ALG-03) meet the PCT constraints. Furthermore, Figures 4.1 to 4.3 suggest that the PCT models employed in the algorithm calculations perform sufficiently well for most glasses, especially when the release concentrations are relatively low and the glasses are within the compositional ranges used to develop the PCT models. The models, however, noticeably under-predict at high PCT releases. The glass HLW-ALG-03, which is outside the compositional range for Phase 1 PCT models development, has normalized PCT releases of B and Li that do not meet the hard property constraints of 16.7 g/l for B and 9.6 g/l for Li, with the predicted normalized releases significantly below the measured values (e.g., 5.03 g/l predicted for B, compared with the measured value of 21.90 g/l). The relatively unsatisfactory performance of the PCT models at high release concentrations, however, is perhaps not unexpected since it has been noted previously during model development that there is a general deficiency of data in the high PCT release regions [8]. More importantly, the PCT model employed in the formulation algorithm is an interim model which has yet to incorporate all of the HLW modeling data. For example, the design range for Na_2O in Phase 1 HLW models development was 3.7 wt% to 20.0 wt%. However, the interim PCT models were developed using a subset of the data that only ranged from 5.0 wt% to 14.0 wt% Na_2O, while all algorithm glasses with large under-prediction for PCT releases have high Na_2O contents (> 14 wt%) that exceed the modeling range. Future model updates are set to make use of all available data. Additionally, the high alkali contents in the algorithm glasses were driven primarily by the $T_{1\%}$ constraint and the $T_{1\%}$ model will also be updated.

4.3 Viscosity and Electrical Conductivity Results

Table 4.4 lists the measured and fitted viscosity results of 39 HLW algorithm glasses (one glass showed non-newtonian behavior over the entire temperature range and is excluded; crystallization was suspected as the cause of the non-newtonian behavior but was not further investigated), and Table 4.5 lists the measured and fitted electrical conductivity results of all 40 algorithm glasses. Figures 4.4 and 4.5, respectively, compare the fitted viscosity at 1150°C and 1100°C with the algorithm predictions at the corresponding temperatures. The respective constraint limits are also included in the figures.

Figures 4.4 and 4.5 show that the agreement between the predicted and measured viscosity values is far from satisfactory. Many of the predicted viscosity values at 1150°C are near the lower constraint limit of 20 P because of the high alkali contents used in order to meet the $T_{1\%}$ constraint. Figure 4.4 shows that a good portion of those glasses with low predicted viscosity values in fact fail to meet the lower constraint limit (the upper constraint limit is not exceeded, see Table 4.3). All HLW algorithm glasses meet the constraint limits for η_{1100}, which are less restrictive. As is the case with PCT modeling, the preliminary viscosity model was developed with only a subset of available data and future updates of the model are expected to improve the predictions. Table 4.3 shows that most of the HLW algorithm glasses that do not meet the viscosity constraints are compositionally outside the range used to develop the Phase 1 viscosity models.

Figures 4.6 and 4.7 compare the fitted electrical conductivity with the predicted values at 1100°C and 1200°C, respectively. It is seen that one glass failed to meet the constraint limits at 1100°C while seven glasses were outside the limits at 1200°C. All the HLW algorithm glasses that do not meet the electrical conductivity constraints are outside the compositional range used to develop the Phase 1 conductivity model (see Table 4.3). Several of the glasses that exceeded the conductivity limits also did not meet the viscosity and/or PCT constraint limits (see Table 4.3), suggesting again the importance of expanding the validity ranges of the property models used in the algorithm.

4.4 Heat-Treatment and One-Percent Crystal Fraction Temperature ($T_{1\%}$) Results

Heat treatment of the HLW algorithm glasses was conducted between 650°C and 1200°C (time duration = 70 hours, after 1 hour at 1200°C for all heat-treatment temperatures other than 1200°C) at selected temperatures that were normally 50°C apart. Table 4.6 lists the measured crystal vol% data. Fitting of these data to a regression equation of the form

$$T = a_0 + a_1X, \tag{4.1}$$

where T = temperature,
X = volume % crystallinity at temperature T,
a_0 = fitted intercept,
a_1 = fitted slope,

provided estimates of $T_{1\%}$ for the algorithm glasses. Table 4.7 presents the regression results (i.e., a_0 and a_1 in Equation 4.1), estimated $T_{1\%}$, and identification of the dominant crystalline phases near $T_{1\%}$. Plots of the crystallization data along with the linear regressions are given in Appendix A. Figure 4.8 compares the estimated $T_{1\%}$ values with the values predicted by the algorithm calculation.

The collected heat-treatment data show the same general characteristics that have been observed previously in HLW modeling studies [8]. The typical relationship found between crystal vol% and heat treatment temperature is relatively simple and can be adequately described by a linear relationship (Equation 4.1). In some cases, the temperature dependence is non-linear and the data may show a change of sign of the slope. This change is presumably due to the increases in melt viscosity at lower temperatures, which reduces the rate of crystallization, preventing the system from reaching equilibrium during the experimental duration (70 hours). In a few other cases, the data show an abrupt change of slope, characteristic of the appearance of a second phase. Similar observations were noted previously [8]. In contrast, the current data set shows more scatter and more frequent occurrences of insignificant crystallization. Consequently, the estimates of $T_{1\%}$ in a few cases were based on relatively few points (as few as two); in other cases, large extrapolation was necessary (see Table 4.7). Nevertheless, it is still possible to estimate $T_{1\%}$ based on the linear trend defined by crystallization of the predominant phase at around 1 vol%, with omission of the data points that clearly depart from the linear trend for the reasons described above.

Overall, $T_{1\%}$ was estimated for 32 of the 40 algorithm glasses. The other eight glasses did not show sufficient crystallization even at low temperatures to allow estimation of $T_{1\%}$; they are considered to meet the constraint limit of ≤ 950°C. Figure 4.8 shows that the estimated $T_{1\%}$ values are well correlated with the primary crystalline phases: when the primary phase is spinel, the $T_{1\%}$ values are estimated to be ≤ 1000°C, when the primary phase is non-spinel (mainly zirconium- and thorium-containing phases), the estimated $T_{1\%}$ are normally ≥ 1000°C. Table 4.3 identifies the algorithm glasses that crystallized non-spinel phases. This clearly demonstrates the need for the formulation algorithm to constrain the formation of non-spinel phases with some of the current waste composition projections. However, when spinel is the primary phase, the formulation algorithm performs reasonably well in confining the $T_{1\%}$ of calculated glasses to ≤ 950°C — only two glasses tested exceed the constraint limit (955.1°C for HLW-ALG-06, which is outside the compositional range used in Phase 1 model development, and 991.7°C for HLW-ALG-14).

For glasses with an elevated constraint limit of $T_{1\%}$ ≤1075°C, the formulation algorithm performed comparatively well when the primary phase is spinel (Figure 4.8). As is the case with the other property-composition models, future update of the $T_{1\%}$ model is expected to improve performance of the IHLW formulation algorithm.

4.5 Testing of Canister Centerline Cooled Glass Samples

After completion of the testing described above, 10 HLW algorithm glasses were selected to undergo the HLW canister centerline cooling (CCC) treatment. The resulting CCC samples were examined for secondary phases and tested for PCT releases. The selection included glasses with high PCT releases (e.g., HLW-ALG-34 with normalized PCT B release of 14.15 g/l) and/or a low ratio of $SiO_2/(SiO_2+Na_2O+Al_2O_3)$ (e.g., HLW-AL-27 with a ratio of 0.55).

Table 4.8 provides the PCT data of the 10 CCC samples and Table 4.9 lists the SEM examination results of the same glasses. Figure 4.9 is a comparison of the PCT normalized boron releases of the CCC samples with their respective as-melted (air quenched) counterparts. It is seen that the PCT data of the CCC samples are generally comparable with the untreated glasses, while the crysallinity data in Table 4.9 are consistent with the heat-treatment data in Table 4.6. The two notable exceptions are HLW-ALG-27 and HLW-ALG-33: the normalized B release, for example, from HLW-ALG-27 is 1.93 g/l, compared with 37.68 g/l for the CCC sample (the corresponding numbers for HLW-ALG-33 are 0.63 g/l and 7.59 g/l). These large increases in PCT releases can be explained by the presence of large amounts of nepheline ($NaAlSiO_4$) in

CCC samples. Figure 4.10 shows the presence of $NaAlSiO_4$ in the CCC sample of HLW-ALG-27. It is expected that heavy crystallization of nepheline during canister cooling could also significantly impact the product performance with respect to TCLP testing (the current work scope does not include TCLP testing).

Since the formation of $NaAlSiO_4$ during CCC sufficiently alters the product durability in some glasses (the sample HLW-ALG-27CCC fails to meet all three PCT constraint limits), an additional constraint to limit the formation of $NaAlSiO_4$ may be needed in the IHLW formulation algorithm.

SECTION 5
SUMMARY AND CONCLUSIONS

In order to support the development of IHLW formulation algorithm at the WTP, testing of glass compositions that were generated by the *preliminary* IHLW algorithm was performed to assess their acceptability with respect to the various product- and process-related requirements and the need for additional constraints. Over 100 glass compositions were calculated using the IHLW formulation algorithm (version 3) with different sources of waste compositions. These glass compositions were supplied to VSL, from which a total of 40 glasses were selected for fabrication and testing. The selection was based on considerations of the compositions (i.e., glasses that occupy previously untested compositional regions were selected) and the predicted properties. Extremes in compositions and/or properties were preferred in glass selection in order to explore the boundaries and limitations of applicability of the algorithm. The testing included measurement of PCT releases, melt viscosity, electrical conductivity, and estimates of $T_{1\%}$ using heat-treatment data. The collected data were compared to the various constraint limits to determine if the glass compositions were acceptable to treat HLW at the WTP.

Of the 40 HLW algorithm glasses tested, 20 did not meet one or more of the constraint requirements. This resulted primarily because: (1) constraints were not used in the formulation algorithm to limit the formation of non-spinel (i.e., zirconium- and thorium-containing) phases, (2) the preliminary PCT models under-predicted the PCT releases when the releases were high, (3) the preliminary viscosity model over-predicted for some glasses that were close to the lower constraint target of $\eta_{1150} \geq 20$ P, and (4) the preliminary electrical conductivity model under-predicted for some glasses that were near the upper constraint target of $\varepsilon_{1150} \leq 0.7$ S/cm. Furthermore, it was discovered that the formation of nepheline ($NaAlSiO_4$) during canister cooling may be important in some instances since it may greatly diminish the product durability.

The fact that a good proportion of the glasses tested did not meet all the constraint requirements, however, does not necessarily suggest that the preliminary formulation algorithm performs unsatisfactorily. Indeed the algorithm works reasonably well for glass compositions that are limited to the ranges used in developing the Phase 1 property-composition models and are limited by iron (instead of zirconium or thorium). A review of the present data shows that the majority of the glasses that do not meet one or more constraint requirements are either outside the modeling compositional range or crystallize Zr- and Th-containing phases (Table 4.3). The collected data will be of value in updating and refining the various property-composition models since they provide additional coverage on the more extreme composition regions. It is therefore important, as items (2) to (4) above clearly demonstrate, to ensure that the validity ranges of various models are wide enough to encompass the expected glass compositions. For the present testing with the preliminary IHLW formulation algorithm, the total alkali (and sodium in particular) and Al_2O_3 concentrations are frequently higher than those found in the data that supported the development of the preliminary property models. Updates of these preliminary models, with already-collected data, will considerably expand the glass compositional regions that can be covered by the IHLW formulation algorithm. Two additional areas are recommended for further improvement of the IHLW algorithm: (1) a constraint should be included to limit the formation of zirconium- and thorium-phases if some of the current waste projections are found to be realistic, and (2) a constraint that limits the formation of $NaAlSiO_4$ also needs to be considered to avoid its adverse impact on product quality. Subsequent versions of the IHLW algorithm are expected to take advantage of the testing data to better define the validity and applicability ranges, while future testing of algorithm glasses will be directed towards validation of the algorithm as applied to the anticipated ranges of WTP glass compositions and properties.

SECTION 6
QUALITY ASSURANCE

This work was conducted under a quality assurance program compliant with Nuclear Quality Assurance (NQA)-1 (1989) and NQA-2a (1990) subpart 2.7, and the *Quality Assurance Requirements and Description* (QARD) Document (DOE/RW-0333P, Rev. 13) [24]. This program is supplemented by a Quality Assurance Project Plan for RPP-WTP work performed at VSL [25]. Test and procedure requirements by which the testing activities are planned and controlled are also defined in that plan. The program is supported by VSL standard operating procedures that were used for this work [26].

The following specific areas of this work are subject to the QARD: glass preparation, glass compositional analysis, and PCT testing. All work in these areas was performed according to VSL QA program and implementing procedures that are compliant with QARD. Since TCLP testing was not part of the current work scope, requirements found in “Quality Assurance Project Plan for Testing Programs Generating Environmental Regulatory Data,” PL-24590-QA00001, (WTP QAPjP) were not applicable.

SECTION 7
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Table 2.1. Glass Property (Hard) Constraints in IHLW Formulation Algorithm.

Property	Constraint	Unit	Reference
PCT Normalized B Release	$r_B + U^{(a)} < 16.7$	g/l	[9]
PCT Normalized Li Release	$r_{Li} + U < 9.6$	g/l	[9]
PCT Normalized Na Release	$r_{Na} + U < 13.3$	g/l	[9]
TCLP Cd Concentration	$c_{Cd} + U < 0.48$	mg/l	[27]
Mass Fraction of Tl_2O in Glass	$g_{Tl2O} < 0.145$	wt%	[28]
Mass Fraction of Sb_2O_3 in Glass	$g_{Sb2O3} < 1.2$	wt%	[27]
Liquidus Temperature	$T_{1\%} + U \leq 950$ºC	ºC	[29]
Viscosity at 1150ºC	$20 \leq \eta_{1150} \pm U \leq 80$	P	none
Viscosity at 1100ºC	$10 \leq \eta_{1100} + U \leq 150$	P	[29]
Electrical Conductivity at 1100ºC	$0.2 \leq \varepsilon_{1100} - U \leq 0.7$	S/cm	[29]
Electrical Conductivity at 1200ºC	$0.2 \leq \varepsilon_{1200} + U \leq 0.7$	S/cm	[29]

(a) U = Uncertainty.
(b) $T_{1\%}$ = Temperature at which the melt is in equilibrium with 1 vol% of solid phase(s).

Table 2.2. Glass Component (Hard) Constraints in IHLW Formulation Algorithm.

Oxide	Lower Limit	Upper Limit
Al_2O_3	1.92	13
B_2O_3	4.8	14
CdO	—[(a)]	1.6
Cr_2O_3	—	0.5
Fe_2O_3	1.92	14
Li_2O	1.92	6
MnO	—	7
Na_2O	3.9	20
NiO	—	1
Sb_2O_3	—	1.2
SiO_2	35	53
SrO	—	10
ThO_2	—	6
Tl_2O	—	0.145
UO_3	—	6.31
ZnO	—	4
ZrO_2	—	9.7

[(a)] — indicates empty data field.

Table 2.3. Waste Loading (Firm) Constraints in IHLW Formulation Algorithm.

Component (s)	Wt% in HLW Glass
Fe_2O_3	12.5
Al_2O_3	11.0
$Na_2O + K_2O$	15.0
ZrO_2	10.0
UO_3[(a)]	8.47
ThO_2	4.0
CaO	7.0
MgO	5.0
BaO	4.0
CdO	3.0
NiO	3.0
PbO	1.0
TiO_2	1.0
Bi_2O_3	2.0
P2O5	3.0
F	1.7
$Al_2O_3 + ZrO_2$	14.0
$Al_2O_3 + Fe_2O_3 + ZrO_2$	21.0
MgO + CaO	8.0
Cr_2O_3	0.5
SO_3	0.5
Ag_2O	0.25
$Rh_2O_3 + RuO_2 + PdO$[(b)]	0.25

[(a)]The Contract TS-1.1 lists UO_2 at 8.0 wt%, which is equivalent to UO_3 at 8.47 wt%.
[(b)]The Contract TS-1.1 lists Ru_2O_3 as a component in the noble metals constraint; it was converted to RuO_2 to be consistent with WTP reporting with no change in the value of the limit.

Table 2.4. Soft Constraints in IHLW Formulation Algorithm.

Constraint	Target Value	Lower Weight	Upper Weight	Comment
$T_{1\%}$ + U[a]	850C	One sided	3	Most constraining factor; also most sensitive to composition fluctuations
r_B + U	4 g/l	One sided	1	None
η_{1150}	50 P	1	1	Roughly mean value for pilot melter tests
Waste Loading Factor	1.03	1	1	Fraction of minimum required waste loading
Mass Fraction of B_2O_3 in Glass (g_{B2O3})	11.02 wt%	1	0.4791	Roughly mean value for pilot melter tests
Mass Fraction of Li_2O in Glass (g_{Li2O})	3.11 wt%	0.4104	1	Roughly mean value for pilot melter tests
Mass Fraction of Na_2O in Glass (g_{Na2O})	12.02 wt%	1	0.3760	Roughly mean value for pilot melter tests
Mass Fraction of SiO_2 in Glass (g_{SiO2})	47.64 wt%	1	0.4241	Roughly mean value for pilot melter tests
Mass Fraction of ZnO in Glass (g_{ZnO})	1.71 wt%	0.7467	1	Roughly mean value for pilot melter tests

[a]U = Uncertainty.

Table 2.5. Compositions of Glass Forming Chemicals (mass oxide per mass GFC).

	Silica	Borax	Na_2CO_3	Li_2CO_3	Hematite	Kyanite	Zincite
Al_2O_3	0.0014	—	—	—	0.015	0.5703	—
B_2O_3	—[a]	0.375	—	—	—	—	—
CaO	0.0001	—	—	—	0.0004	0.0003	—
CdO	—	—	—	—	—	—	0.0001
Cl	—	—	0.0002	0.0001	—	—	—
Cr_2O_3	—	—	—	0.0001	—	—	—
Fe_2O_3	0.0002	—	—	—	0.97	0.0078	—
Li_2O	—	—	—	0.402	—	—	—
MgO	0.0001	—	—	0.0001	0.001	0.0001	—
MnO	—	—	—	—	0.0012	—	—
Na_2O	0.0002	0.167	0.5837	0.0008	—	0.0042	—
P_2O_5	—	—	—	—	0.0027	—	—
SO_3	—	—	0.0001	0.0003	0.0007	—	—
SiO_2	0.997	—	—	—	0.0135	0.4067	—
TiO_2	0.0001	—	—	—	—	0.0079	—
ZnO	—	—	—	—	—	—	0.999

[a] — indicates empty data field.

Table 2.6. HLW Algorithm Glasses Selected for Testing.

Glass ID	Formulation Algorithm ID	Glass Characteristics
HLW-ALG-01	Made Up Glass #2	High Predicted Viscosity.
HLW-ALG-02	Made Up Glass #6	High Predicted Viscosity. Low Predicted PCT Releases.
HLW-ALG-03	Made Up Glass #11	High Total Alkalis. High Predicted PCT Releases.
HLW-ALG-04	Made Up Glass #12	High SiO_2. High Predicted PCT Releases.
HLW-ALG-05	Made Up Glass #13	High MnO and SrO. High Predicted $T_{1\%}$. Several Predicted Properties Near Constraint Limits and High Soft Constraint Penalty.
HLW-ALG-06	Made Up Glass #4	High Predicted $T_{1\%}$. High Soft Constraint Penalty. High TCLP Cd Releases (TCLP not tested).
HLW-ALG-07	Made Up Glass #7	High Predicted η_{1150}+U. Low Predicted PCT Releases. Low Fe_2O_3 (Al_2O_3 + ZrO_2 > 14 wt%).
HLW-ALG-08	Made Up Glass #9	High ZrO_2 and Predicted $T_{1\%}$. High Soft Constraint Penalty.
HLW-ALG-09	High Waste Loading 3.1vv 37	High Waste Loading and Fe_2O_3. High Predicted $T_{1\%}$.
HLW-ALG-10	D8, alk≤21.5%	High Predicted PCT and TCLP (Cd) Releases (TCLP not tested). Constrained Total Alkalis.
HLW-ALG-11	Max WL, 7-MW (Same waste as HLW-ALG-07)	High Waste Loading (50% >HLW-ALG-07). High ThO_2. Low Fe_2O_3 (Al_2O_3 + ZrO_2 ≈ 21 wt%).
HLW-ALG-12	Min η_{T01}, D10	Low Predicted Viscosity.
HLW-ALG-13	Max WL, D3-MW	High UO_3. Medium Al_2O_3 and Fe_2O_3. Low SiO_2.and Total Alkalis.
HLW-ALG-14	Min Immiscibility, D9	Low total alkalis. Low Predicted Viscosity.

Table 2.6. HLW Algorithm Glasses Selected for Testing (continued).

Glass ID	Formulation Algorithm ID	Glass Characteristics
HLW-ALG-15	8-MW, alk≤21.5%	High (Al_2O_3+Fe_2O_3+ZrO_2) (26.36 wt%). Constrained Total Alkalis.
HLW-ALG-16	D5, alk≤21.5%	Low Fe_2O_3. High Predicted Viscosity with Constrained Total Alkalis.
HLW-ALG-17	D6, alk≤21.5%	High Predicted PCT Releases with Constrained Total Alkalis.
HLW-ALG-18	Made Up Glass # 1	High Al_2O_3. High Predicted Viscosity.
HLW-ALG-19	Made Up Glass #11, alk=21.5 (same waste as HLW-ALG-03)	Varied Total Alkalis for Comparison with HLW-ALG-03 and HLW-ALG-20.
HLW-ALG-20	Made Up Glass#11, alk=23.3 (same waste as HLW-ALG-03)	Varied Total Alkalis for Comparison with HLW-ALG-03 and HLW-ALG-19.
HLW-ALG-21	16 Glass-wl	High ThO_2. High Predicted $T_{1\%}$.
HLW-ALG-22	16 Glass-wl, alk = 21.5 (same waste as HLW-ALG-22)	Varied Total Alkalis for Comparison with HLW-ALG-21 and HLW-ALG-23.
HLW-ALG-23	16 Glass-2l, alk = 23.5 (same waste as HLW-ALG-22)	Varied Total Alkalis for Comparison with HLW-ALG-21 and HLW-ALG-22.
HLW-ALG-24	New Glasses, Max WL, D4-MW	High Al_2O_3, ThO_2, UO_3 and ZrO_2 (Meets TS-1.1 Requirements with $Al_2O_3 + ZrO_2 > 14$ wt% and $ThO_2 > 4$ wt%).
HLW-ALG-25	New Glasses, D7, alk≤21.5%	High Cr_2O_3 (Cr_2O_3-limited glass). Low (Al_2O_3+Fe_2O_3+ZrO_2).
HLW-ALG-26	New Glasses, limit EC, D3	Low Total Alkalis. Low Predicted $T_{1\%}$ and Conductivity.
HLW-ALG-27	New Glasses, 1-MW, alk≤21.5% (same waste as HLW-ALG-18)	High Predicted $T_{1\%}$ with Constrained Total Alkalis. Increased Waste Loading vs. HLW-ALG-18.
HLW-ALG-28	New Glasses, 3-MW, alk≤21.5%	High Predicted $T_{1\%}$ with Constrained Total Alkalis.

Table 2.6. HLW Algorithm Glasses Selected for Testing (continued).

Glass ID	Formulation Algorithm ID	Glass Characteristics
HLW-ALG-29	New Glasses, 6-MW, alk≤21.5% (same waste as HLW-ALG-02)	High (Al_2O_3+Fe_2O_3+ZrO_2) (26.89 wt%).
HLW-ALG-30	Actual Waste, AZ-101 Glass	Glass calculated for Actual Waste Composition.
HLW-ALG-31	Newer High T01 Made up Waste Glass #11 (same waste as HLW-ALG-03)	Relaxed $T_{1\%}$ Constraint for Comparison with HLW-ALG-03.
HLW-ALG-32	Newer High T01 Made up Waste Glass #13 (same waste as HLW-ALG-05)	Relaxed $T_{1\%}$ Constraint for Comparison with HLW-ALG-05.
HLW-ALG-33	Newer High T01 8-MW, alk≤21.5% (same waste as HLW-ALG-15)	Relaxed $T_{1\%}$ Constraint for Comparison with HLW-ALG-15. Highest (Al_2O_3+Fe_2O_3+ZrO_2) (30.87 wt%).
HLW-ALG-34	New Glasses, max PCT, D6 (same waste as HLW-ALG-17)	Maximum Predicted PCT Releases.
HLW-ALG-35	High T01 Glasses 3.1vv batch 37 (same waste as HLW-ALG-09)	Relaxed $T_{1\%}$ Constraint for Comparison with HLW-ALG-09.
HLW-ALG-36	Newer High T01 New glasses, min ηT01, D10 (same waste as HLW-ALG-12)	Relaxed $T_{1\%}$ Constraint for Comparison with HLW-ALG-12.
HLW-ALG-37	Newer High T01, limit EC, D3 (same waste as HLW-ALG-26)	Relaxed $T_{1\%}$ Constraint for Comparison with HLW-ALG-26.
HLW-ALG-38	High T01 Glasses, Alt LAW batch 57	Relaxed $T_{1\%}$ Constraint for Comparison with HLW-ALG-39.
HLW-ALG-39	G2 57 - Orp Alt Law Glass (same waste as HLW-ALG-38)	High Predicted Viscosity.
HLW-ALG-40	Newer High T01 AZ101 Glass (same waste as HLW-ALG-30)	Relaxed $T_{1\%}$ Constraint for Comparison with HLW-ALG-30.

Table 2.7. Summary of Waste Compositions, Melter Feed Mix, and Calculated Properties for Selected HLW Algorithm Glasses.

Glass ID		HLW-ALG-01	HLW-ALG-02	HLW-ALG-03	HLW-ALG-04	HLW-ALG-05
Algorithm Formulation ID		Made Up Glass #2	Made Up Glass #6	Made Up Glass #11	Made Up Glass #12	Made Up Glass #13
Waste Composition (wt%)	Al_2O_3	48.50%	33.00%	0.00%	0.00%	4.81%
	CdO	0.00%	0.00%	0.00%	0.00%	3.33%
	Cr_2O_3	2.20%	1.15%	2.15%	3.30%	1.15%
	Fe_2O_3	42.28%	29.66%	54.19%	83.08%	34.82%
	MnO	0.00%	0.00%	9.00%	0.00%	19.20%
	NiO	0.00%	2.17%	4.30%	6.60%	2.17%
	SrO	0.00%	0.00%	0.00%	0.00%	27.50%
	ThO_2	0.00%	0.00%	0.00%	0.00%	0.00%
	UO_3	0.00%	0.00%	0.00%	0.00%	0.00%
	ZrO_2	0.00%	27.00%	23.34%	0.00%	0.00%
	Na_2O	0.00%	0.00%	0.00%	0.00%	0.00%
	SiO_2	0.00%	0.00%	0.00%	0.00%	0.00%
	Others	7.02%	7.02%	7.02%	7.02%	7.02%
Melter Feed Mix (oxide wt%)	Waste oxides	22.69%	24.01%	23.24%	15.15%	35.90%
	Silica	45.31%	44.69%	43.06%	50.58%	46.11%
	Borax	15.04%	15.79%	12.24%	15.93%	6.62%
	Na_2CO_3	12.61%	10.42%	15.15%	11.02%	6.86%
	Li_2CO_3	3.33%	3.55%	3.06%	2.88%	4.28%
	Hematite	0.00%	0.00%	0.00%	0.00%	0.00%
	Kyanite	0.00%	0.00%	3.26%	3.24%	0.23%
	Zincite	1.03%	1.54%	0.00%	1.20%	0.00%
Calculated Glass Properties	r_B+U_{PB} (g/l)	1.340	0.891	5.029	4.458	2.945
	r_{Na}+U_{PNa} (g/l)	1.190	0.756	4.047	2.970	2.355
	r_{Li}+U_{PLi} (g/l)	1.087	0.886	2.888	2.704	2.214
	c_{Cd}+U_{Ptc} (mg/l)	0.000	0.000	0.000	0.000	0.366
	$T_{1\%}$+U_{pt1} (°C)	863.8	853.0	890.7	862.0	949.8
	η_{1150}+U_{Ph} (P)	59.2	59.9	24.4	48.0	24.5
	η_{1150}-U_{Ph} (P)	47.9	51.9	20.4	39.1	20.0
	η_{1100}+U_{Ph} (P)	95.5	96.7	36.9	76.3	37.0
	ε_{1100}-U_{Pe} (S/cm)	0.315	0.309	0.384	0.264	0.200
	ε_{1200}+U_{Pe} (S/cm)	0.479	0.482	0.595	0.429	0.380
Waste Loading Factor		1.000	1.029	1.008	1.007	1.000

Table 2.7. Summary of Waste Compositions, Melter Feed Mix, and Calculated Properties for Selected HLW Algorithm Glasses (continued).

Glass ID		HLW-ALG-06	HLW-ALG-07	HLW-ALG-08	HLW-ALG-09	HLW-ALG-10
Algorithm Formulation ID		Made Up Glass #4	Made Up Glass #7	Made Up Glass #9	High Waste Loading 3.1vv 37	D8, alk≤21.5%
Waste Composition (wt%)	Al_2O_3	24.00%	30.20%	0.00%	11.11%	2.00%
	CdO	3.30%	0.00%	3.30%	0.17%	3.75%
	Cr_2O_3	0.50%	0.00%	1.15%	0.43%	2.20%
	Fe_2O_3	26.48%	0.02%	17.82%	28.52%	48.13%
	MnO	10.00%	8.71%	8.71%	8.02%	30.80%
	NiO	1.20%	0.00%	2.17%	0.39%	4.40%
	SrO	20.00%	15.33%	15.33%	15.32%	0.00%
	ThO_2	4.00%	15.38%	9.80%	1.24%	1.00%
	UO_3	1.50%	0.00%	11.36%	2.79%	0.00%
	ZrO_2	2.00%	23.34%	23.34%	5.25%	0.70%
	Na_2O	0.00%	0.00%	0.00%	17.78%	0.00%
	SiO_2	0.00%	0.00%	0.00%	1.33%	0.00%
	Others	7.02%	7.02%	7.02%	7.66%	7.02%
Melter Feed Mix (oxide wt%)	Waste oxides	40.01%	26.78%	40.82%	48.74%	22.73%
	Silica	37.30%	44.09%	35.38%	38.23%	46.14%
	Borax	6.58%	15.20%	6.58%	6.70%	13.43%
	Na_2CO_3	13.58%	7.06%	11.88%	4.35%	13.23%
	Li_2CO_3	2.52%	3.26%	2.07%	1.97%	2.02%
	Hematite	0.00%	1.98%	0.00%	0.00%	0.00%
	Kyanite	0.00%	0.00%	3.28%	0.00%	2.45%
	Zincite	0.00%	1.63%	0.00%	0.00%	0.00%
Calculated Glass Properties	r_B+U_{PB} (g/l)	1.424	0.765	1.830	1.601	7.368
	r_{Na}+U_{PNa} (g/l)	1.494	0.553	1.506	1.652	5.172
	r_{Li}+U_{PLi} (g/l)	1.085	0.744	1.406	1.239	3.399
	c_{Cd}+U_{Ptc} (mg/l)	0.454	0.000	0.477	0.027	0.480
	$T_{1\%}$+U_{pt1} (°C)	950.0	721.2	950.0	950.0	905.7
	η_{1150}+U_{Ph} (P)	23.0	59.4	23.9	22.9	30.2
	η_{1150}-U_{Ph} (P)	20.0	51.6	20.0	20.0	24.2
	η_{1100}+U_{Ph} (P)	34.6	95.8	36.1	34.4	46.3
	ε_{1100}-U_{Pe} (S/cm)	0.270	0.215	0.272	0.242	0.222
	ε_{1200}+U_{Pe} (S/cm)	0.450	0.373	0.473	0.392	0.392
Waste Loading Factor		1.000	1.030	1.000	1.112	1.000

Table 2.7. Summary of Waste Compositions, Melter Feed Mix, and Calculated Properties for Selected HLW Algorithm Glasses (continued).

Glass ID		HLW-ALG-11	HLW-ALG-12	HLW-ALG-13	HLW-ALG-14	HLW-ALG-15
Algorithm Formulation ID		Max WL, 7-MW	min η_{T01}, D10	Max WL, D3-MW	min Immisc., D9	8-MW, alk≤21.5%
Waste Composition (wt%)	Al_2O_3	30.20%	14.50%	10.00%	4.05%	33.00%
	CdO	0.00%	1.00%	0.10%	4.25%	0.00%
	Cr_2O_3	0.00%	0.70%	0.01%	0.00%	1.15%
	Fe_2O_3	0.02%	30.88%	11.77%	35.81%	33.32%
	MnO	8.71%	5.00%	5.00%	19.20%	0.00%
	NiO	0.00%	2.00%	0.10%	2.17%	2.17%
	SrO	15.33%	15.00%	10.00%	27.50%	0.00%
	ThO_2	15.38%	4.00%	9.00%	0.00%	0.00%
	UO_3	0.00%	4.00%	10.00%	0.00%	0.00%
	ZrO_2	23.34%	5.90%	15.00%	0.00%	23.34%
	Na_2O	0.00%	5.00%	12.00%	0.00%	0.00%
	SiO_2	0.00%	5.00%	10.00%	0.00%	0.00%
	Others	7.02%	7.02%	7.02%	7.02%	7.02%
Melter Feed Mix (oxide wt%)	Waste oxides	39.01%	40.52%	61.15%	34.90%	29.27%
	Silica	35.05%	38.34%	28.95%	46.14%	37.45%
	Borax	17.23%	6.58%	6.40%	6.63%	19.98%
	Na_2CO_3	0.72%	11.82%	0.17%	2.72%	11.39%
	Li_2CO_3	6.01%	2.74%	3.34%	6.01%	1.92%
	Hematite	1.98%	0.00%	0.00%	0.00%	0.00%
	Kyanite	0.00%	0.00%	0.00%	3.60%	0.00%
	Zincite	0.00%	0.00%	0.00%	0.00%	0.00%
Calculated Glass Properties	r_B+U_{PB} (g/l)	0.690	1.822	0.703	1.521	1.131
	$r_{Na}+U_{PNa}$ (g/l)	0.396	1.859	0.562	1.203	0.852
	$r_{Li}+U_{PLi}$ (g/l)	0.722	1.375	0.747	1.540	0.926
	$c_{Cd}+U_{Ptc}$ (mg/l)	0.000	0.116	0.016	0.351	0.000
	$T_{1\%}+U_{pt1}$ (°C)	870.0	950.0	950.0	949.3	950.0
	$\eta_{1150}+U_{Ph}$ (P)	25.4	22.7	23.2	24.3	43.8
	$\eta_{1150}-U_{Ph}$ (P)	21.3	20.0	20.0	20.0	36.6
	$\eta_{1100}+U_{Ph}$ (P)	38.6	34.2	34.9	36.7	69.1
	$\varepsilon_{1100}-U_{Pe}$ (S/cm)	0.254	0.314	0.243	0.200	0.266
	$\varepsilon_{1200}+U_{Pe}$ (S/cm)	0.468	0.495	0.422	0.375	0.428
Waste Loading Factor		1.500	1.001	1.376	1.000	1.250

Table 2.7. Summary of Waste Compositions, Melter Feed Mix, and Calculated Properties for Selected HLW Algorithm Glasses (continued).

Glass ID		HLW-ALG-16	HLW-ALG-17	HLW-ALG-18	HLW-ALG-19	HLW-ALG-20
Algorithm Formulation ID		D5, alk≤21.5%	D6, alk≤21.5%	Made Up Glass #1	Made Up Glass #11, alk=21.5	Made Up Glass #11, alk=23.3
Waste Composition (wt%)	Al_2O_3	41.00%	0.00%	48.50%	0.00%	0.00%
	CdO	0.10%	0.10%	0.00%	0.00%	0.00%
	Cr_2O_3	2.00%	2.21%	0.00%	2.15%	2.15%
	Fe_2O_3	16.88%	55.07%	44.48%	54.19%	54.19%
	MnO	0.00%	30.50%	0.00%	9.00%	9.00%
	NiO	3.00%	4.40%	0.00%	4.30%	4.30%
	SrO	0.00%	0.00%	0.00%	0.00%	0.00%
	ThO_2	0.00%	0.00%	0.00%	0.00%	0.00%
	UO_3	0.00%	0.00%	0.00%	0.00%	0.00%
	ZrO_2	15.00%	0.70%	0.00%	23.34%	23.34%
	Na_2O	5.00%	0.00%	0.00%	0.00%	0.00%
	SiO_2	10.00%	0.00%	0.00%	0.00%	0.00%
	Others	7.02%	7.02%	7.02%	7.02%	7.02%
Melter Feed Mix (oxide wt%)	Waste oxides	25.00%	22.62%	23.25%	23.25%	23.25%
	Silica	41.28%	44.56%	46.01%	45.26%	45.63%
	Borax	19.76%	14.72%	15.82%	13.72%	10.98%
	Na_2CO_3	10.03%	12.83%	9.90%	11.86%	13.97%
	Li_2CO_3	2.02%	2.02%	3.44%	2.66%	2.92%
	Hematite	0.16%	0.00%	0.00%	0.00%	0.00%
	Kyanite	0.00%	3.25%	0.00%	3.25%	3.25%
	Zincite	1.75%	0.00%	1.58%	0.00%	0.00%
Calculated Glass Properties	r_B+U_{PB} (g/l)	0.998	8.359	0.909	2.722	3.096
	$r_{Na}+U_{PNa}$ (g/l)	0.781	5.610	0.775	2.075	2.607
	$r_{Li}+U_{PLi}$ (g/l)	0.855	3.665	0.851	1.922	2.140
	$c_{Cd}+U_{Ptc}$ (mg/l)	0.012	0.014	0.000	0.000	0.000
	$T_{1\%}+U_{pt1}$ (°C)	860.5	939.6	852.5	944.4	925.8
	$\eta_{1150}+U_{Ph}$ (P)	80.9	24.7	57.1	44.4	40.7
	$\eta_{1150}-U_{Ph}$ (P)	64.4	20.0	51.2	37.0	34.0
	$\eta_{1100}+U_{Ph}$ (P)	133.7	37.3	91.9	70.1	64.0
	$\varepsilon_{1100}-U_{Pe}$ (S/cm)	0.249	0.223	0.262	0.274	0.323
	$\varepsilon_{1200}+U_{Pe}$ (S/cm)	0.403	0.388	0.397	0.427	0.500
Waste Loading Factor		1.000	1.000	1.029	1.008	1.008

Table 2.7. Summary of Waste Compositions, Melter Feed Mix, and Calculated Properties for Selected HLW Algorithm Glasses (continued).

Glass ID		HLW-ALG-21	HLW-ALG-22	HLW-ALG-23	HLW-ALG-24	HLW-ALG-25
Algorithm Formulation ID		16 Glass-wl	16 Glass-wl, alk=21.5	16 Glass-wl, alk=23.5	New Glasses-Max WL, D4-MW	New Glasses-D7, alk≤21.5%
Waste Composition (wt%)	Al_2O_3	5.98%	5.98%	5.98%	20.00%	2.00%
	CdO	0.31%	0.31%	0.31%	0.10%	0.10%
	Cr_2O_3	1.15%	1.15%	1.15%	0.01%	2.20%
	Fe_2O_3	22.49%	22.49%	22.49%	0.27%	51.78%
	MnO	2.76%	2.76%	2.76%	5.00%	30.80%
	NiO	1.26%	1.26%	1.26%	0.10%	4.40%
	SrO	0.04%	0.04%	0.04%	6.50%	0.00%
	ThO_2	13.73%	13.73%	13.73%	9.00%	1.00%
	UO_3	10.49%	10.49%	10.49%	9.00%	0.00%
	ZrO_2	20.77%	20.77%	20.77%	14.50%	0.70%
	Na_2O	10.83%	10.83%	10.83%	12.50%	0.00%
	SiO_2	3.40%	3.40%	3.40%	16.00%	0.00%
	Others	6.81%	6.81%	6.81%	7.02%	7.02%
Melter Feed Mix (oxide wt%)	Waste oxides	42.84%	42.34%	40.71%	62.53%	22.73%
	Silica	37.53%	37.26%	38.14%	25.02%	45.49%
	Borax	6.08%	8.67%	6.12%	6.38%	14.37%
	Na_2CO_3	11.07%	9.32%	12.96%	0.00%	12.94%
	Li_2CO_3	2.48%	2.41%	2.07%	4.25%	2.02%
	Hematite	0.00%	0.00%	0.00%	1.81%	0.00%
	Kyanite	0.00%	0.00%	0.00%	0.00%	2.46%
	Zincite	0.00%	0.00%	0.00%	0.00%	0.00%
Calculated Glass Properties	r_B+U_{PB} (g/l)	3.389	3.242	4.087	0.395	8.000
	$r_{Na}+U_{PNa}$ (g/l)	2.673	2.330	3.292	0.343	5.418
	$r_{Li}+U_{PLi}$ (g/l)	2.099	2.005	2.345	0.503	3.560
	$c_{Cd}+U_{Ptc}$ (mg/l)	0.045	0.046	0.046	0.018	0.014
	$T_{1\%}+U_{pt1}$ (°C)	950.0	950.0	890.6	950.0	924.6
	$\eta_{1150}+U_{Ph}$ (P)	24.1	24.1	24.0	41.3	26.6
	$\eta_{1150}-U_{Ph}$ (P)	20.0	20.0	20.0	34.3	21.5
	$\eta_{1100}+U_{Ph}$ (P)	36.4	36.4	36.2	64.9	40.5
	$\varepsilon_{1100}-U_{Pe}$ (S/cm)	0.406	0.361	0.421	0.267	0.221
	$\varepsilon_{1200}+U_{Pe}$ (S/cm)	0.651	0.581	0.672	0.489	0.388
Waste Loading Factor		1.470	1.4536	1.397	1.541	1.000

Table 2.7. Summary of Waste Compositions, Melter Feed Mix, and Calculated Properties for Selected HLW Algorithm Glasses (continued).

Glass ID		HLW-ALG-26	HLW-ALG-27	HLW-ALG-28	HLW-ALG-29	HLW-ALG-30
Algorithm Formulation ID		New Glasses-limit EC, D3	New Glasses-1-MW, alk≤21.5%	New Glasses-3-MW, alk≤21.5%	New Glasses-6-MW, alk≤21.5%	Actual Waste, AZ101 Glass
Waste Composition (wt%)	Al_2O_3	10.00%	48.50%	32.80%	33.00%	23.10%
	CdO	0.10%	0.00%	0.00%	0.00%	2.03%
	Cr_2O_3	0.01%	0.00%	1.20%	1.15%	0.45%
	Fe_2O_3	11.77%	44.48%	48.08%	29.66%	35.38%
	MnO	5.00%	0.00%	8.70%	0.00%	1.04%
	NiO	0.10%	0.00%	2.20%	2.17%	1.56%
	SrO	10.00%	0.00%	0.00%	0.00%	0.49%
	ThO_2	9.00%	0.00%	0.00%	0.00%	0.00%
	UO_3	10.00%	0.00%	0.00%	0.00%	2.93%
	ZrO_2	15.00%	0.00%	0.00%	27.00%	10.74%
	Na_2O	12.00%	0.00%	0.00%	0.00%	10.83%
	SiO_2	10.00%	0.00%	0.00%	0.00%	3.81%
	Others	7.02%	7.02%	7.02%	7.02%	7.64%
Melter Feed Mix (oxide wt%)	Waste oxides	45.70%	26.70%	26.73%	29.86%	31.09%
	Silica	38.65%	37.72%	39.96%	36.87%	43.78%
	Borax	10.38%	20.00%	20.00%	19.97%	13.67%
	Na_2CO_3	0.90%	11.39%	11.39%	11.39%	7.72%
	Li_2CO_3	3.02%	1.92%	1.92%	1.92%	3.10%
	Hematite	0.00%	0.00%	0.00%	0.00%	0.00%
	Kyanite	0.00%	0.00%	0.00%	0.00%	0.00%
	Zincite	1.36%	2.28%	0.00%	0.00%	0.64%
Calculated Glass Properties	r_B+U_{PB} (g/l)	0.709	1.486	2.781	1.014	1.094
	$r_{Na}+U_{PNa}$ (g/l)	0.534	1.103	1.948	0.768	0.975
	$r_{Li}+U_{PLi}$ (g/l)	0.758	1.044	1.593	0.868	0.998
	$c_{Cd}+U_{Ptc}$ (mg/l)	0.013	0.000	0.000	0.000	0.176
	$T_{1\%}+U_{pt1}$ (°C)	807.7	950.0	950.0	950.0	871.6
	$\eta_{1150}+U_{Ph}$ (P)	44.8	30.5	26.3	47.2	46.2
	$\eta_{1150}-U_{Ph}$ (P)	39.7	26.2	22.8	39.0	42.3
	$\eta_{1100}+U_{Ph}$ (P)	70.7	46.8	39.9	75.0	73.2
	$\varepsilon_{1100}-U_{Pe}$ (S/cm)	0.200	0.249	0.244	0.267	0.289
	$\varepsilon_{1200}+U_{Pe}$ (S/cm)	0.338	0.392	0.376	0.439	0.428
Waste Loading Factor		1.028	1.182	1.029	1.280	1.025

Table 2.7. Summary of Waste Compositions, Melter Feed Mix, and Calculated Properties for Selected HLW Algorithm Glasses (continued).

Glass ID		HLW-ALG-31	HLW-ALG-32	HLW-ALG-33	HLW-ALG-34	HLW-ALG-35
Algorithm Formulation ID		High T01 Madeup Waste Glass #11	High T01 Madeup Waste Glass #13	High T01 8-MW, alk ≤ 21.5%	New Glasses-Max PCT, D6	High T01 Glasses 3.1 vv batch 37
Waste Composition (wt%)	Al_2O_3	0.00%	4.81%	33.00%	0.00%	11.11%
	CdO	0.00%	3.33%	0.00%	0.10%	0.17%
	Cr_2O_3	2.15%	1.15%	1.15%	2.21%	0.43%
	Fe_2O_3	54.19%	34.82%	33.32%	55.07%	28.52%
	MnO	9.00%	19.20%	0.00%	30.50%	8.02%
	NiO	4.30%	2.17%	2.17%	4.40%	0.39%
	SrO	0.00%	27.50%	0.00%	0.00%	15.32%
	ThO_2	0.00%	0.00%	0.00%	0.00%	1.24%
	UO_3	0.00%	0.00%	0.00%	0.00%	2.79%
	ZrO_2	23.34%	0.00%	23.34%	0.70%	5.25%
	Na_2O	0.00%	0.00%	0.00%	0.00%	17.78%
	SiO_2	0.00%	0.00%	0.00%	0.00%	1.33%
	Others	7.02%	7.02%	7.02%	7.02%	7.66%
Melter Feed Mix (oxide wt%)	Waste oxides	23.24%	36.36%	34.28%	22.62%	49.07%
	Silica	46.37%	38.17%	36.55%	45.09%	40.28%
	Borax	15.51%	6.62%	11.24%	11.66%	6.69%
	Na_2CO_3	6.89%	7.22%	14.15%	15.36%	0.00%
	Li_2CO_3	3.08%	3.97%	3.78%	2.02%	2.79%
	Hematite	0.00%	0.00%	0.00%	0.00%	0.00%
	Kyanite	3.25%	7.32%	0.00%	3.25%	0.00%
	Zincite	1.66%	0.35%	0.00%	0.00%	1.17%
Calculated Glass Properties	r_B+U_{PB} (g/l)	1.579	1.405	0.865	9.020	0.785
	$r_{Na}+U_{PNa}$ (g/l)	1.082	1.314	0.884	6.824	0.788
	$r_{Li}+U_{PLi}$ (g/l)	1.382	1.228	0.861	3.912	0.819
	$c_{Cd}+U_{Ptc}$ (mg/l)	0.000	0.395	0.000	0.014	0.023
	$T_{1\%}+U_{pt1}$ (°C)	1061.4	1075.0	1075.0	924.1	1045.9
	$\eta_{1150}+U_{Ph}$ (P)	59.9	23.8	38.1	24.7	31.8
	$\eta_{1150}-U_{Ph}$ (P)	49.6	20.0	30.7	20.0	28.0
	$\eta_{1100}+U_{Ph}$ (P)	96.8	36.0	59.6	37.4	49.1
	$\varepsilon_{1100}-U_{Pe}$ (S/cm)	0.208	0.200	0.403	0.255	0.200
	$\varepsilon_{1200}+U_{Pe}$ (S/cm)	0.332	0.359	0.656	0.441	0.326
Waste Loading Factor		1.008	1.013	1.464	1.000	1.119

Table 2.7. Summary of Waste Compositions, Melter Feed Mix, and Calculated Properties for Selected HLW Algorithm Glasses (continued).

Glass ID		HLW-ALG-36	HLW-ALG-37	HLW-ALG-38	HLW-ALG-39	HLW-ALG-40
Algorithm Formulation ID		High T01 - min η T01, D10	Newer High T01 Limit EC, D3	High T01 Glasses Alt LAW batch 57	G2 57-Orp Alt Law Glass	Newer High T01 AZ101 Glass
Waste Composition (wt%)	Al_2O_3	14.50%	10.00%	5.98%	5.98%	23.10%
	CdO	1.00%	0.10%	0.31%	0.31%	2.03%
	Cr_2O_3	0.70%	0.01%	1.15%	1.15%	0.45%
	Fe_2O_3	30.88%	11.77%	22.49%	22.49%	35.38%
	MnO	5.00%	5.00%	2.76%	2.76%	1.04%
	NiO	2.00%	0.10%	1.26%	1.26%	1.56%
	SrO	15.00%	10.00%	0.04%	0.04%	0.49%
	ThO_2	4.00%	9.00%	13.73%	13.73%	0.00%
	UO_3	4.00%	10.00%	10.49%	10.49%	2.93%
	ZrO_2	5.90%	15.00%	20.77%	20.77%	10.74%
	Na_2O	5.00%	12.00%	10.83%	10.83%	10.83%
	SiO_2	5.00%	10.00%	3.40%	3.40%	3.81%
	Others	7.02%	7.02%	6.81%	6.81%	7.64%
Melter Feed Mix (oxide wt%)	Waste oxides	44.65%	61.35%	43.49%	31.07%	39.54%
	Silica	35.95%	28.93%	40.11%	46.90%	38.95%
	Borax	9.00%	6.39%	10.52%	14.10%	11.94%
	Na_2CO_3	7.50%	0.00%	2.66%	3.31%	6.37%
	Li_2CO_3	2.90%	2.57%	2.88%	3.11%	3.05%
	Hematite	0.00%	0.00%	0.33%	0.00%	0.00%
	Kyanite	0.00%	0.00%	0.00%	0.00%	0.00%
	Zincite	0.00%	0.77%	0.00%	1.51%	0.15%
Calculated Glass Properties	r_B+U_{PB} (g/l)	1.145	0.570	1.317	1.498	0.713
	$r_{Na}+U_{PNa}$ (g/l)	1.048	0.452	0.838	0.936	0.683
	$r_{Li}+U_{PLi}$ (g/l)	0.992	0.639	1.156	1.275	0.748
	$c_{Cd}+U_{Ptc}$ (mg/l)	0.117	0.017	0.032	0.028	0.198
	$T_{1\%}+U_{pt1}$ (°C)	1075.0	1004.7	1075.0	851.2	1075.0
	$\eta_{1150}+U_{Ph}$ (P)	22.8	29.8	48.1	59.9	44.9
	$\eta_{1150}-U_{Ph}$ (P)	20.0	25.5	39.2	50.7	39.1
	$\eta_{1100}+U_{Ph}$ (P)	34.3	45.6	76.3	96.7	70.9
	$\varepsilon_{1100}-U_{Pe}$ (S/cm)	0.249	0.200	0.223	0.217	0.268
	$\varepsilon_{1200}+U_{Pe}$ (S/cm)	0.397	0.353	0.378	0.362	0.418
Waste Loading Factor		1.103	1.380	1.493	1.066	1.304

Table 2.8. Target Compositions (wt%) of HLW Algorithm Glasses[(a)].

	HLW-ALG-01	HLW-ALG-02	HLW-ALG-03	HLW-ALG-04	HLW-ALG-05
Ag_2O	0.046%	0.048%	0.047%	0.030%	0.072%
Al_2O_3	**11.086%**[(b)]	8.001%[(b)]	1.926%	1.926%	1.927%
B_2O_3	10.560%	11.088%	8.621%	11.134%	4.810%
BaO	0.035%	0.037%	0.036%	—	0.056%
Bi_2O_3	—[(c)]	—	—	—	—
CaO	0.331%	0.350%	0.339%	0.224%	0.521%
CdO	—	—	—	—	1.198%
Ce_2O_3	0.050%	0.053%	0.051%	0.033%	0.079%
Cl	—	—	—	—	—
Cr_2O_3	**0.501%**	0.278%	**0.501%**	**0.501%**	0.415%
Cs_2O	—	—	—	—	—
CuO	—	—	—	—	—
F	0.032%	0.033%	0.032%	—	0.050%
Fe_2O_3	9.619%	7.145%	**12.650%**	**12.639%**	**12.536%**
K_2O	0.124%	0.132%	0.127%	0.083%	0.197%
La_2O_3	0.101%	0.107%	0.103%	0.067%	0.160%
Li_2O	3.329%	3.550%	3.057%	2.876%	4.286%
MgO	0.096%	0.101%	0.098%	0.066%	0.149%
MnO	—	—	2.095%	—	6.906%
Na_2O	17.280%	15.318%	18.966%	15.980%	8.937%
Nd_2O_3	0.085%	0.090%	0.087%	0.057%	0.134%
NiO	—	0.522%	1.001%	1.001%	0.781%
P_2O_5	0.096%	0.101%	0.098%	0.064%	0.151%
PbO	0.202%	0.214%	0.207%	0.135%	0.320%
PdO	—	—	—	—	—
Pr_2O_3	—	—	—	—	0.027%
Rb_2O	—	—	—	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	0.028%	0.030%	0.029%	—	0.045%
SO_3	0.052%	0.055%	0.054%	0.036%	0.080%
SiO_2	45.286%	44.674%	44.365%	51.881%	46.197%
SrO	—	—	—	—	9.891%
ThO_2	—	—	—	—	—
TiO_2	—	—	0.043%	0.039%	0.026%
UO_3	—	—	—	—	—
WO_3	—	—	—	—	—
ZnO	1.062%	1.577%	0.032%	1.226%	0.050%
ZrO_2	—	6.495%	5.433%	—	—
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

[(a)] Oxide compositions are rounded to 3 decimal places.
[(b)] Boldface indicates component meets TS-1.1 constraint by itself; underline indicates component meets constraint as part of a group.
[(c)]— indicates empty data field.

Table 2.8. Target Compositions (wt%) of HLW Algorithm Glasses[(a)] (continued).

	HLW-ALG-06	HLW-ALG-07	HLW-ALG-08	HLW-ALG-09	HLW-ALG-10
Ag_2O	0.080%	0.054%	0.082%	0.053%	0.046%
Al_2O_3	9.670%[(b)]	8.194%[(b)]	1.926%	5.480%	1.926%
B_2O_3	4.807%	10.704%	4.807%	4.808%	9.448%
BaO	0.062%	0.042%	0.064%	0.080%	0.035%
Bi_2O_3	—[(c)]	—	—	—	—
CaO	0.579%	0.390%	0.591%	0.560%	0.332%
CdO	1.322%	—	1.349%	0.084%	0.854%
Ce_2O_3	0.088%	0.059%	0.090%	0.124%	0.050%
Cl	—	—	—	0.050%	—
Cr_2O_3	0.201%	—	0.471%	0.211%	**0.501%**
Cs_2O	0.025%	—	0.026%	—	—
CuO	0.025%	—	0.026%	—	—
F	0.056%	0.037%	0.057%	0.076%	0.032%
Fe_2O_3	10.620%	1.928%	7.318%	**13.931%**	10.984%
K_2O	0.219%	0.147%	0.224%	0.354%	0.125%
La_2O_3	0.178%	0.119%	0.182%	0.387%	0.101%
Li_2O	2.530%	3.258%	2.081%	1.987%	2.020%
MgO	0.164%	0.114%	0.167%	0.492%	0.096%
MnO	4.007%	2.339%	3.560%	3.916%	7.010%
Na_2O	15.635%	11.777%	13.943%	15.116%	17.410%
Nd_2O_3	0.149%	0.100%	0.152%	0.299%	0.085%
NiO	0.481%	—	0.887%	0.189%	1.001%
P_2O_5	0.169%	0.118%	0.172%	0.204%	0.096%
PbO	0.357%	0.239%	0.364%	0.410%	0.203%
PdO	—	—	—	—	—
Pr_2O_3	0.030%	—	0.031%	0.028%	—
Rb_2O	—	—	—	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	0.050%	0.034%	0.051%	—	0.028%
SO_3	0.088%	0.061%	0.089%	0.229%	0.051%
SiO_2	37.279%	44.110%	36.699%	38.868%	47.112%
SrO	8.015%	4.113%	6.267%	7.479%	—
ThO_2	1.603%	**4.126%**	**4.006%**	0.603%	0.228%
TiO_2	0.025%	—	0.052%	—	0.036%
UO_3	0.601%	—	4.644%	1.360%	—
WO_3	0.026%	—	0.026%	—	—
ZnO	0.055%	1.675%	0.056%	0.059%	0.031%
ZrO_2	0.801%	6.262%	9.541%	2.565%	0.159%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

(a) Oxide compositions are rounded to 3 decimal places.
(b) Boldface indicates component meets TS-1.1 constraint by itself; underline indicates component meets constraint as part of a group.
(c)— indicates empty data field.

Table 2.8. Target Compositions (wt%) of HLW Algorithm Glasses[a] (continued).

	HLW-ALG-11	HLW-ALG-12	HLW-ALG-13	HLW-ALG-14	HLW-ALG-15
Ag_2O	0.078%	0.081%	0.123%	0.070%	0.059%
Al_2O_3	**11.886%**[b]	5.938%	6.166%[b]	3.543%	9.731%
B_2O_3	12.188%	4.807%	4.808%	4.809%	14.029%
BaO	0.061%	0.063%	0.095%	0.054%	0.046%
Bi_2O_3	—[c]	—	0.033%	—	—
CaO	0.565%	0.586%	0.882%	0.507%	0.424%
CdO	—	0.406%	0.061%	1.486%	—
Ce_2O_3	0.086%	0.089%	0.135%	0.077%	0.065%
Cl	—	—	0.028%	—	—
Cr_2O_3	—	0.285%	—	—	0.338%
Cs_2O	—	0.025%	0.038%	—	—
CuO	—	0.026%	0.039%	—	—
F	0.054%	0.056%	0.085%	0.048%	0.041%
Fe_2O_3	1.928%	**12.540%**	7.216%	**12.562%**	9.780%
K_2O	0.214%	0.222%	0.335%	0.191%	0.161%
La_2O_3	0.174%	0.180%	0.272%	0.155%	0.130%
Li_2O	6.013%	2.750%	3.354%	6.012%	1.928%
MgO	0.163%	0.166%	0.247%	0.146%	0.121%
MnO	3.408%	2.029%	3.063%	6.715%	—
Na_2O	6.065%	15.899%	9.504%	4.804%	17.583%
Nd_2O_3	0.146%	0.151%	0.228%	0.130%	0.109%
NiO	—	0.812%	0.061%	0.759%	0.636%
P_2O_5	0.170%	0.171%	0.258%	0.147%	0.124%
PbO	0.348%	0.361%	0.545%	0.311%	0.261%
PdO	—	—	—	—	—
Pr_2O_3	0.029%	0.031%	0.046%	0.026%	—
Rb_2O	—	—	—	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	0.049%	0.051%	0.077%	0.044%	0.037%
SO_3	0.088%	0.089%	0.130%	0.078%	0.065%
SiO_2	35.076%	40.350%	35.058%	47.605%	37.449%
SrO	5.994%	6.087%	6.125%	9.618%	—
ThO_2	**6.013%**	1.623%	**5.513%**	—	—
TiO_2	—	0.026%	0.036%	0.052%	—
UO_3	—	1.623%	6.125%	—	—
WO_3	0.025%	0.026%	0.040%	—	—
ZnO	0.054%	0.056%	0.084%	0.048%	0.040%
ZrO_2	9.125%	2.394%	9.188%	—	6.845%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

[a] Oxide compositions are rounded to 3 decimal places.
[b] Boldface indicates component meets TS-1.1 constraint by itself; underline indicates component meets constraint as part of a group.
[c]— indicates empty data field.

Table 2.8. Target Compositions (wt%) of HLW Algorithm Glasses[(a)] (continued).

	HLW-ALG-16	HLW-ALG-17	HLW-ALG-18	HLW-ALG-19	HLW-ALG-20
Ag_2O	0.050%	0.045%	0.047%	0.047%	0.047%
Al_2O_3	10.329%[(b)]	1.926%	**11.360%[(b)]**	1.926%	1.926%
B_2O_3	13.850%	10.338%	11.109%	9.652%	7.754%
BaO	0.039%	0.035%	0.036%	0.036%	0.036%
Bi_2O_3	—[(c)]	—	—	—	—
CaO	0.363%	0.331%	0.339%	0.340%	0.340%
CdO	0.025%	—	—	—	—
Ce_2O_3	0.055%	0.050%	0.051%	0.051%	0.051%
Cl	—	—	—	—	—
Cr_2O_3	**0.501%**	**0.501%**	—	**0.501%**	**0.501%**
Cs_2O	—	—	—	—	—
CuO	—	—	—	—	—
F	0.035%	0.031%	0.032%	0.032%	0.032%
Fe_2O_3	4.396%	**12.515%**	10.369%	**12.652%**	**12.651%**
K_2O	0.137%	0.124%	0.128%	0.127%	0.127%
La_2O_3	0.111%	0.101%	0.103%	0.103%	0.103%
Li_2O	2.021%	2.020%	3.437%	2.659%	2.926%
MgO	0.104%	0.095%	0.098%	0.098%	0.098%
MnO	—	6.912%	—	2.096%	2.095%
Na_2O	17.406%	17.414%	14.807%	16.131%	17.400%
Nd_2O_3	0.093%	0.085%	0.087%	0.087%	0.087%
NiO	0.751%	0.997%	—	1.001%	1.001%
P_2O_5	0.106%	0.095%	0.098%	0.098%	0.098%
PbO	0.223%	0.202%	0.207%	0.207%	0.207%
PdO	—	—	—	—	—
Pr_2O_3	—	—	—	—	—
Rb_2O	—	—	—	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	0.031%	0.028%	0.029%	0.029%	0.029%
SO_3	0.056%	0.051%	0.053%	0.053%	0.053%
SiO_2	43.773%	45.869%	45.993%	46.563%	46.929%
SrO	—	—	—	—	—
ThO_2	—	—	—	—	—
TiO_2	—	0.043%	—	0.043%	0.043%
UO_3	—	—	—	—	—
WO_3	—	—	—	—	—
ZnO	1.786%	0.031%	1.616%	0.032%	0.032%
ZrO_2	3.757%	0.159%	—	5.434%	5.434%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

[(a)] Oxide compositions are rounded to 3 decimal places.
[(b)] Boldface indicates component meets TS-1.1 constraint by itself; underline indicates component meets constraint as part of a group.
[(c)]— indicates empty data field.

Table 2.8. Target Compositions (wt%) of HLW Algorithm Glasses[(a)] (continued).

	HLW-ALG-21	HLW-ALG-22	HLW-ALG-23	HLW-ALG-24	HLW-ALG-25
Ag_2O	0.140%	0.138%	0.133%	0.126%	0.046%
Al_2O_3	2.619%[(b)]	2.588%	2.492%	**12.589%[(b)]**	1.926%
B_2O_3	4.810%	6.599%	4.809%	4.808%	10.096%
BaO	0.048%	0.048%	0.046%	0.097%	0.035%
Bi_2O_3	—[(c)]	—	—	0.034%	—
CaO	0.642%	0.635%	0.611%	0.902%	0.332%
CdO	0.131%	0.129%	0.124%	0.063%	—
Ce_2O_3	0.049%	0.049%	0.047%	0.138%	0.050%
Cl	—	—	—	0.029%	—
Cr_2O_3	0.493%	0.487%	0.469%	—	**0.501%**
Cs_2O	—	—	—	0.039%	—
CuO	0.034%	0.033%	0.032%	0.040%	—
F	0.039%	0.038%	0.037%	0.087%	0.032%
Fe_2O_3	9.663%	9.548%	9.180%	1.927%	11.817%
K_2O	0.174%	0.172%	0.165%	0.343%	0.125%
La_2O_3	0.136%	0.135%	0.130%	0.278%	0.101%
Li_2O	2.475%	2.407%	2.069%	4.265%	2.020%
MgO	0.112%	0.111%	0.107%	0.255%	0.096%
MnO	1.186%	1.172%	1.127%	3.134%	7.012%
Na_2O	17.623%	16.615%	19.298%	9.813%	17.414%
Nd_2O_3	0.103%	0.101%	0.097%	0.234%	0.085%
NiO	0.542%	0.535%	0.515%	0.063%	1.002%
P_2O_5	0.118%	0.117%	0.112%	0.269%	0.096%
PbO	0.180%	0.178%	0.171%	0.558%	0.203%
PdO	—	—	—	—	—
Pr_2O_3	—	—	—	0.047%	—
Rb_2O	0.030%	0.029%	0.028%	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	—	—	—	0.078%	0.029%
SO_3	0.121%	0.120%	0.116%	0.135%	0.051%
SiO_2	38.986%	38.701%	39.517%	35.060%	46.478%
SrO	—	—	—	4.071%	—
ThO_2	**5.894%**	**5.824%**	**5.599%**	**5.637%**	0.228%
TiO_2	0.027%	0.027%	0.026%	0.036%	0.036%
UO_3	4.502%	4.449%	4.278%	5.637%	—
WO_3	0.123%	0.121%	0.116%	0.040%	—
ZnO	0.084%	0.083%	0.079%	0.086%	0.031%
ZrO_2	8.915%	8.809%	8.469%	9.082%	0.159%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

[(a)] Oxide compositions are rounded to 3 decimal places.
[(b)] Boldface indicates component meets TS-1.1 constraint by itself; underline indicates component meets constraint as part of a group.
[(c)]— indicates empty data field.

Table 2.8. Target Compositions (wt%) of HLW Algorithm Glasses[(a)] (continued).

	HLW-ALG-26	HLW-ALG-27	HLW-ALG-28	HLW-ALG-29	HLW-ALG-30
Ag_2O	0.092%	0.054%	0.054%	0.060%	0.037%
Al_2O_3	4.632%	**13.025%**[(b)]	8.839%[(b)]	9.926%	7.250%
B_2O_3	7.474%	14.027%	14.027%	14.030%	9.597%
BaO	0.071%	0.042%	0.042%	0.047%	0.065%
Bi_2O_3	—[(c)]	—	—	—	—
CaO	0.661%	0.387%	0.388%	0.433%	0.422%
CdO	0.046%	—	—	—	0.631%
Ce_2O_3	0.101%	0.059%	0.059%	0.066%	0.233%
Cl	—	—	—	—	0.058%
Cr_2O_3	—	—	0.322%	0.345%	0.141%
Cs_2O	0.029%	—	—	—	—
CuO	0.029%	—	—	—	0.029%
F	0.063%	0.037%	0.037%	0.041%	—
Fe_2O_3	5.397%	11.905%	**12.884%**	8.882%	11.020%
K_2O	0.251%	0.146%	0.147%	0.164%	0.133%
La_2O_3	0.203%	0.119%	0.119%	0.133%	0.259%
Li_2O	3.024%	1.928%	1.928%	1.928%	3.099%
MgO	0.187%	0.111%	0.111%	0.123%	0.102%
MnO	2.289%	—	2.330%	—	0.323%
Na_2O	9.610%	17.589%	17.589%	17.581%	15.321%
Nd_2O_3	0.171%	0.100%	0.100%	0.112%	0.190%
NiO	0.046%	—	0.589%	0.649%	0.485%
P_2O_5	0.193%	0.113%	0.113%	0.126%	0.393%
PbO	0.408%	0.238%	0.238%	0.266%	0.073%
PdO	—	—	—	—	0.101%
Pr_2O_3	0.035%	—	—	—	—
Rb_2O	—	—	—	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	0.057%	0.033%	0.034%	0.037%	0.075%
SO_3	0.098%	0.059%	0.059%	0.066%	—
SiO_2	43.210%	37.713%	39.956%	36.865%	44.901%
SrO	4.578%	—	—	—	0.153%
ThO_2	**4.120%**	—	—	—	—
TiO_2	0.029%	—	—	—	—
UO_3	4.578%	—	—	—	0.911%
WO_3	0.030%	—	—	—	—
ZnO	1.427%	2.316%	0.037%	0.041%	0.654%
ZrO_2	6.866%	—	—	8.079%	3.343%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

(a) Oxide compositions are rounded to 3 decimal places.
(b) Boldface indicates component meets TS-1.1 constraint by itself; underline indicates component meets constraint as part of a group.
(c)— indicates empty data field.

Table 2.8. Target Compositions (wt%) of HLW Algorithm Glasses[(a)] (continued).

	HLW-ALG-31	HLW-ALG-32	HLW-ALG-33	HLW-ALG-34	HLW-ALG-35
Ag_2O	0.047%	0.073%	0.069%	0.046%	0.053%
Al_2O_3	1.926%	6.000%	<u>**11.389%**</u>[(b)]	1.926%	<u>5.519%</u>[(b)]
B_2O_3	10.888%	4.810%	8.006%	8.223%	4.808%
BaO	0.036%	0.057%	0.053%	0.035%	0.080%
Bi_2O_3	—[(c)]	—	—	—	—
CaO	0.340%	0.529%	0.497%	0.331%	0.564%
CdO	—	1.213%	—	—	0.085%
Ce_2O_3	0.051%	0.080%	0.076%	0.050%	0.125%
Cl	—	—	—	—	0.049%
Cr_2O_3	**0.501%**	0.420%	0.396%	**0.501%**	0.212%
Cs_2O	—	—	—	—	—
CuO	—	—	—	—	—
F	0.032%	0.051%	0.048%	0.031%	0.076%
Fe_2O_3	**12.650%**	**12.753%**	<u>11.456%</u>	**12.515%**	<u>**14.024%**</u>
K_2O	0.127%	0.200%	0.188%	0.124%	0.356%
La_2O_3	0.103%	0.162%	0.153%	0.101%	0.390%
Li_2O	3.078%	3.972%	3.783%	2.020%	2.801%
MgO	0.098%	0.151%	0.141%	0.096%	0.495%
MnO	2.095%	6.996%	—	6.912%	3.942%
Na_2O	11.711%	9.317%	17.656%	19.002%	10.818%
Nd_2O_3	0.087%	0.136%	0.128%	0.085%	0.301%
NiO	1.001%	0.791%	0.746%	0.997%	0.190%
P_2O_5	0.098%	0.153%	0.145%	0.095%	0.205%
PbO	0.207%	0.324%	0.306%	0.202%	0.413%
PdO	—	—	—	—	—
Pr_2O_3	—	0.027%	0.026%	—	0.028%
Rb_2O	—	—	—	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	0.029%	0.046%	0.043%	0.028%	—
SO_3	0.052%	0.080%	0.077%	0.051%	0.230%
SiO_2	47.666%	41.153%	36.552%	46.396%	40.921%
SrO	—	10.020%	—	—	7.529%
ThO_2	—	—	—	—	0.607%
TiO_2	0.043%	0.082%	—	0.043%	—
UO_3	—	—	—	—	1.369%
WO_3	—	—	—	—	—
ZnO	1.699%	0.404%	0.047%	0.031%	1.228%
ZrO_2	5.433%	—	<u>8.019%</u>	0.159%	<u>2.582%</u>
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

[(a)] Oxide compositions are rounded to 3 decimal places.
[(b)] Boldface indicates component meets TS-1.1 constraint by itself; underline indicates component meets constraint as part of a group.
[(c)]— indicates empty data field.

Table 2.8. Target Compositions (wt%) of HLW Algorithm Glasses[(a)] (continued).

	HLW-ALG-36	HLW-ALG-37	HLW-ALG-38	HLW-ALG-39	HLW-ALG-40
Ag_2O	0.090%	0.123%	0.142%	0.102%	0.047%
Al_2O_3	<u>6.536%</u>[(b)]	<u>6.186%</u>	<u>2.661%</u>	1.927%	<u>9.195%</u>
B_2O_3	6.511%	4.808%	7.901%	10.207%	8.436%
BaO	0.070%	0.096%	0.049%	0.035%	0.082%
Bi_2O_3	—[(c)]	0.033%	—	—	—
CaO	0.645%	0.884%	0.652%	0.468%	0.535%
CdO	0.447%	0.062%	0.133%	0.095%	0.802%
Ce_2O_3	0.099%	0.135%	0.050%	0.036%	0.297%
Cl	—	0.028%	—	—	0.073%
Cr_2O_3	0.314%	—	**0.501%[(b)]**	0.358%	0.179%
Cs_2O	0.028%	0.039%	—	—	—
CuO	0.028%	0.039%	0.034%	—	0.037%
F	0.062%	0.085%	0.039%	0.028%	—
Fe_2O_3	**<u>13.819%</u>**	<u>7.240%</u>	<u>9.809%</u>	7.012%	**<u>14.008%</u>**
K_2O	0.245%	0.336%	0.176%	0.126%	0.170%
La_2O_3	0.199%	0.273%	0.139%	0.099%	0.329%
Li_2O	2.903%	2.580%	2.880%	3.110%	3.054%
MgO	0.182%	0.248%	0.114%	0.084%	0.128%
MnO	2.236%	3.072%	1.204%	0.860%	0.411%
Na_2O	12.535%	9.358%	10.641%	11.054%	14.348%
Nd_2O_3	0.167%	0.229%	0.104%	0.074%	0.242%
NiO	0.894%	0.061%	0.550%	0.393%	0.616%
P_2O_5	0.188%	0.259%	0.120%	0.086%	0.499%
PbO	0.398%	0.547%	0.183%	0.131%	0.092%
PdO	—	—	—	—	0.128%
Pr_2O_3	0.034%	0.046%	—	—	—
Rb_2O	—	—	0.030%	—	—
Rh_2O_3	—	—	—	—	0.031%
RuO_2	0.056%	0.077%	—	—	0.096%
SO_3	0.097%	0.130%	0.122%	0.088%	—
SiO_2	38.173%	35.059%	41.588%	47.962%	40.399%
SrO	6.709%	6.145%	—	—	0.195%
ThO_2	1.789%	**5.530%**	**5.983%**	**4.274%**	—
TiO_2	0.028%	0.036%	0.028%	—	—
UO_3	1.789%	6.145%	4.570%	3.265%	1.158%
WO_3	0.029%	0.040%	0.124%	0.089%	—
ZnO	0.062%	0.853%	0.420%	1.572%	0.162%
ZrO_2	<u>2.639%</u>	<u>9.217%</u>	<u>9.050%</u>	6.465%	<u>4.250%</u>
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

[(a)] Oxide compositions are rounded to 3 decimal places.
[(b)] Boldface indicates component meets TS-1.1 constraint by itself; underline indicates component meets constraint as part of a group.
[(c)]— indicates empty data field.

Table 3.1. HLW Canister Centerline Cooling (CCC) Temperature Profile.

Segment	Time (min)	Start Temperature (ºC)	Cooling Rate (ºC/min)
1	0−45	1050	−1.556
2	45−107	980	−0.806
3	107−200	930	−0.591
4	200−329	875	−0.388
5	329−527	825	−0.253
6	527−707	775	−0.278
7	707−1776	725	−0.304

Table 4.1. Compositional Analysis (wt%) of HLW Algorithm Glasses by XRF[(a)].

Oxides	HLW-ALG-01	HLW-ALG-02	HLW-ALG-03	HLW-ALG-04	HLW-ALG-05
Ag_2O	0.06%	0.05%	0.06%	0.04%	0.10%
Al_2O_3	11.60%	8.82%	3.02%	3.34%	3.90%
As_2O_5	—[(b)]	—	—	0.01%	—
Au	—	—	0.00%	—	—
B_2O_3	**10.56%**[(c)]	**11.09%**	**8.62%**	**11.13%**	**4.81%**
BaO	0.03%	0.04%	0.03%	—	—
Bi_2O_3	—	—	—	—	—
CaO	0.37%	0.38%	0.40%	0.27%	0.56%
CdO	—	—	—	—	1.29%
Ce_2O_3	0.05%	0.07%	0.06%	0.04%	0.09%
Cl	—	—	—	0.00%	—
CoO	0.00%	0.01%	—	0.01%	—
Cr_2O_3	0.57%	0.33%	0.61%	0.62%	0.49%
Cs_2O	—	—	—	—	—
CuO	—	—	—	—	—
Er_2O_3	0.01%	0.01%	0.01%	0.02%	0.02%
Eu_2O_3	—	—	—	—	0.02%
Fe_2O_3	9.03%	6.79%	12.43%	12.47%	12.35%
Gd_2O_3	—	0.01%	—	—	—
GeO_2	—	0.00%	—	—	0.01%
HfO_2	—	0.15%	0.14%	—	—
HgO	—	—	—	—	0.01%
Ho_2O_3	—	0.01%	—	—	—
IrO_2	—	—	—	0.01%	—
K_2O	0.21%	0.24%	0.22%	0.19%	0.31%
La_2O_3	0.07%	0.10%	0.07%	0.05%	0.17%
Li_2O	**3.33%**	**3.55%**	**3.06%**	**2.88%**	**4.29%**
MgO	0.10%	0.10%	0.13%	0.06%	0.20%
MnO	0.00%	—	2.15%	0.02%	6.98%
MoO_3	—	0.01%	—	—	—
Na_2O	17.65%	15.55%	18.67%	15.83%	8.51%
Nd_2O_3	0.09%	0.12%	0.11%	0.08%	0.13%
NiO	—	0.49%	0.98%	0.97%	0.76%
P_2O_5	0.14%	0.15%	0.14%	0.14%	0.19%
PbO	0.17%	0.19%	0.21%	0.13%	0.32%
PdO	—	—	—	—	—
Pr_2O_3	—	—	—	—	0.04%
Rb_2O	—	0.00%	—	—	—
Re_2O_7	—	—	—	—	0.02%
Rh_2O_3	—	—	—	—	—
RuO_2	0.03%	0.03%	0.02%	—	0.03%
SO_3	0.07%	0.06%	0.07%	0.05%	0.08%
SeO_2	—	0.01%	0.01%	—	—
SiO_2	44.80%	44.34%	43.36%	50.27%	44.00%
Sm_2O_3	—	0.01%	—	0.02%	0.03%
SnO_2	—	—	0.01%	—	—
SrO	0.02%	0.02%	0.02%	0.04%	9.96%
Tb_4O_7	0.01%	0.01%	—	0.02%	0.026%
ThO_2	—	—	—	—	—
TiO_2	0.03%	0.04%	0.08%	0.08%	0.10%
UO_3	—	—	—	—	—
WO_3	—	—	—	—	—
Y_2O_3	—	0.01%	—	0.00%	—
Yb_2O_3	—	—	—	0.01%	—
ZnO	0.97%	1.46%	0.05%	1.19%	0.06%
ZrO_2	—	5.76%	5.28%	0.03%	0.02%
TOTAL	100.0%	100.0%	100.0%	100.0%	99.9%

[(a)] Compositional values are rounded to 2 decimal places.
[(b)] — indicates empty data field.
[(c)] Boldface indicates target values are used for B_2O_3 and Li_2O, which were not measured by XRF.

Table 4.1. Compositional Analysis (wt%) of HLW Algorithm Glasses by XRF[(a)] (continued).

Oxides	HLW-ALG-06	HLW-ALG-07	HLW-ALG-08	HLW-ALG-09	HLW-ALG-10
Ag_2O	0.13%	0.08%	0.11%	0.07%	0.07%
Al_2O_3	9.33%	8.54%	2.63%	5.58%	2.99%
As_2O_5	—[(b)]	—	—	—	0.01%
Au	0.01%	—	—	—	—
B_2O_3	**4.81%**[(c)]	**10.70%**	**4.81%**	**4.81%**	**9.45%**
BaO	—	—	—	—	0.04%
Bi_2O_3	—	—	—	—	—
CaO	0.69%	0.46%	0.67%	0.66%	0.39%
CdO	1.54%	—	1.51%	0.10%	0.91%
Ce_2O_3	0.12%	0.07%	0.12%	0.16%	0.06%
Cl	—	—	—	0.05%	0.01%
CoO	—	—	—	0.01%	0.01%
Cr_2O_3	0.27%	—	0.62%	0.27%	0.62%
Cs_2O	0.02%	—	—	—	—
CuO	0.08%	0.04%	0.05%	0.01%	0.02%
Er_2O_3	—	—	—	0.01%	0.02%
Eu_2O_3	—	—	—	—	0.02%
Fe_2O_3	11.61%	2.12%	7.80%	14.86%	11.06%
Gd_2O_3	—	—	—	—	—
GeO_2	0.01%	—	—	—	—
HfO_2	0.04%	0.17%	0.28%	0.08%	—
HgO	0.01%	—	—	—	—
Ho_2O_3	—	—	—	—	—
IrO_2	—	—	—	—	—
K_2O	0.33%	0.31%	0.33%	0.49%	0.28%
La_2O_3	—	—	0.18%	0.35%	0.06%
Li_2O	**2.53%**	**3.26%**	**2.08%**	**1.99%**	**2.02%**
MgO	0.12%	0.08%	0.14%	0.38%	0.06%
MnO	4.50%	2.54%	3.87%	4.29%	7.27%
MoO_3	—	—	—	0.02%	—
Na_2O	13.86%	10.15%	12.36%	13.76%	16.16%
Nd_2O_3	0.20%	0.14%	0.19%	0.40%	0.11%
NiO	0.52%	—	0.96%	0.20%	1.02%
P_2O_5	0.24%	0.18%	0.24%	0.27%	0.17%
PbO	0.39%	0.25%	0.39%	0.45%	0.20%
PdO	—	—	—	—	—
Pr_2O_3	0.06%	—	0.07%	0.05%	—
Rb_2O	—	—	—	—	—
Re_2O_7	0.02%	—	—	—	—
Rh_2O_3	—	—	—	0.01%	—
RuO_2	0.05%	0.04%	0.03%	—	0.03%
SO_3	0.12%	0.06%	0.08%	0.24%	0.08%
SeO_2	—	0.00%	0.01%	—	—
SiO_2	36.30%	43.95%	34.91%	37.34%	46.27%
Sm_2O_3	—	—	—	0.03%	0.03%
SnO_2	—	—	—	—	0.01%
SrO	8.75%	4.33%	6.65%	8.03%	0.03%
Tb_4O_7	0.02%	—	—	0.02%	0.03%
ThO_2	1.70%	4.26%	4.12%	0.61%	0.22%
TiO_2	—	—	0.07%	—	0.06%
UO_3	0.66%	—	5.03%	1.51%	—
WO_3	—	—	—	—	—
Y_2O_3	—	—	—	—	—
Yb_2O_3	—	—	—	—	0.01%
ZnO	0.06%	1.77%	0.06%	0.08%	0.04%
ZrO_2	0.84%	6.43%	9.61%	2.69%	0.17%
TOTAL	99.9%	99.9%	100.0%	99.9%	100.0%

(a) Compositional values are rounded to 2 decimal places.
(b) — indicates empty data field.
(c) Boldface indicates target values are used for B_2O_3 and Li_2O, which were not measured by XRF.

Table 4.1. Compositional Analysis (wt%) of HLW Algorithm Glasses by XRF[(a)] (continued).

Oxides	HLW-ALG-11	HLW-ALG-12	HLW-ALG-13	HLW-ALG-14	HLW-ALG-15
Ag_2O	0.10%	0.12%	0.16%	0.13%	0.08%
Al_2O_3	12.15%	6.40%	6.60%	4.93%	9.98%
As_2O_5	—[(b)]	—	—	—	—
Au	—	—	—	—	—
B_2O_3	**12.19%**[(c)]	**4.81%**	**4.81%**	**4.81%**	**14.03%**
BaO	—	—	—	—	0.05%
Bi_2O_3	—	—	0.05%	—	—
CaO	0.68%	0.66%	0.99%	0.63%	0.49%
CdO	—	0.44%	0.05%	1.65%	—
Ce_2O_3	0.10%	0.12%	0.17%	0.08%	0.09%
Cl	—	—	0.02%	—	—
CoO	—	0.01%	0.00%	0.01%	0.00%
Cr_2O_3	—	0.37%	—	—	0.43%
Cs_2O	—	0.03%	0.04%	—	—
CuO	0.01%	0.05%	0.06%	—	—
Er_2O_3	—	0.02%	0.01%	0.02%	0.01%
Eu_2O_3	0.01%	—	—	0.02%	—
Fe_2O_3	2.19%	12.59%	7.30%	12.57%	9.67%
Gd_2O_3	—	—	—	—	—
GeO_2	—	—	—	0.01%	0.00%
HfO_2	0.21%	0.07%	0.26%	—	0.20%
HgO	—	—	—	0.01%	—
Ho_2O_3	—	—	—	—	—
IrO_2	—	—	—	—	—
K_2O	0.33%	0.34%	0.44%	0.32%	0.25%
La_2O_3	0.20%	—	—	0.18%	0.09%
Li_2O	**6.01%**	**2.75%**	**3.35%**	**6.01%**	**1.93%**
MgO	0.14%	0.09%	0.25%	0.13%	0.12%
MnO	3.82%	2.19%	3.31%	6.94%	0.02%
MoO_3	—	—	0.05%	—	0.02%
Na_2O	5.75%	14.78%	9.03%	4.61%	16.73%
Nd_2O_3	0.20%	0.20%	0.28%	0.17%	0.15%
NiO	—	0.86%	0.07%	0.76%	0.64%
P_2O_5	0.27%	0.24%	0.31%	0.24%	0.20%
PbO	0.38%	0.37%	0.57%	0.32%	0.27%
PdO	—	—	—	—	—
Pr_2O_3	0.06%	0.05%	0.08%	0.04%	—
Rb_2O	—	—	—	—	—
Re_2O_7	—	—	—	0.02%	—
Rh_2O_3	—	—	—	—	—
RuO_2	0.03%	0.04%	0.11%	0.06%	0.04%
SO_3	0.08%	0.25%	0.18%	0.10%	0.17%
SeO_2	—	—	0.01%	—	—
SiO_2	35.64%	39.78%	34.62%	45.40%	37.74%
Sm_2O_3	—	—	—	0.02%	—
SnO_2	—	0.02%	—	—	0.02%
SrO	6.45%	6.33%	6.28%	9.52%	0.04%
Tb_4O_7	—	—	—	0.02%	0.01%
ThO_2	5.42%	1.67%	5.34%	—	—
TiO_2	0.04%	—	—	0.11%	0.02%
UO_3	—	1.72%	6.18%	—	—
WO_3	—	—	0.05%	—	—
Y_2O_3	—	—	—	—	0.01%
Yb_2O_3	—	—	—	—	—
ZnO	0.06%	0.10%	0.11%	0.06%	0.08%
ZrO_2	7.40%	2.46%	8.82%	—	6.43%
TOTAL	99.9%	99.9%	99.9%	99.9%	100.0%

(a) Compositional values are rounded to 2 decimal places.
(b) — indicates empty data field.
(c) Boldface indicates target values are used for B_2O_3 and Li_2O, which were not measured by XRF.

Table 4.1. Compositional Analysis (wt%) of HLW Algorithm Glasses by XRF[(a)] (continued).

Oxides	HLW-ALG-16	HLW-ALG-17	HLW-ALG-18	HLW-ALG-19	HLW-ALG-20
Ag_2O	0.08%	0.06%	0.08%	0.09%	0.07%
Al_2O_3	10.87%	2.53%	11.20%	2.68%	2.54%
As_2O_5	—[(b)]	0.01%	—	—	—
Au	—	—	—	—	—
B_2O_3	**13.85%**[(c)]	**10.34%**	**11.11%**	**9.65%**	**7.75%**
BaO	0.04%	0.04%	0.05%	0.04%	0.04%
Bi_2O_3	—	—	—	—	—
CaO	0.42%	0.45%	0.41%	0.40%	0.40%
CdO	—	—	—	—	—
Ce_2O_3	0.05%	0.05%	0.06%	0.04%	0.06%
Cl	—	—	—	—	—
CoO	—	0.01%	—	0.01%	0.01%
Cr_2O_3	0.62%	0.64%	0.01%	0.64%	0.63%
Cs_2O	—	—	—	—	—
CuO	—	—	—	—	—
Er_2O_3	—	0.02%	0.01%	0.02%	0.01%
Eu_2O_3	—	0.03%	—	—	—
Fe_2O_3	4.19%	12.45%	10.66%	12.66%	12.58%
Gd_2O_3	—	—	—	—	—
GeO_2	—	—	—	—	0.01%
HfO_2	0.09%	—	—	0.15%	0.15%
HgO	—	—	—	—	—
Ho_2O_3	—	—	—	—	0.01%
IrO_2	—	0.00%	—	—	—
K_2O	0.25%	0.23%	0.24%	0.24%	0.24%
La_2O_3	0.07%	0.10%	0.07%	0.07%	0.08%
Li_2O	**2.02%**	**2.02%**	**3.44%**	**2.66%**	**2.93%**
MgO	0.09%	0.08%	0.08%	0.07%	0.09%
MnO	—	7.36%	—	2.25%	2.23%
MoO_3	0.01%	—	—	0.01%	0.01%
Na_2O	17.34%	16.47%	14.10%	15.46%	16.66%
Nd_2O_3	0.12%	0.09%	0.11%	0.11%	0.11%
NiO	0.72%	1.04%	—	1.05%	1.04%
P_2O_5	0.19%	0.18%	0.18%	0.22%	0.18%
PbO	0.21%	0.19%	0.22%	0.20%	0.22%
PdO	—	—	—	—	—
Pr_2O_3	—	—	—	—	—
Rb_2O	—	—	—	—	—
Re_2O_7	—	—	—	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	0.05%	0.02%	0.05%	0.04%	0.04%
SO_3	0.11%	0.24%	0.22%	0.23%	0.21%
SeO_2	0.01%	—	—	0.01%	—
SiO_2	43.30%	44.93%	45.80%	45.52%	46.02%
Sm_2O_3	0.01%	0.03%	0.02%	—	—
SnO_2	0.01%	0.03%	0.03%	0.02%	0.03%
SrO	0.02%	0.02%	0.02%	0.02%	0.02%
Tb_4O_7	—	0.02%	0.02%	—	—
ThO_2	—	—	—	—	—
TiO_2	0.03%	0.08%	0.02%	0.07%	0.07%
UO_3	—	—	—	—	—
WO_3	—	—	—	—	—
Y_2O_3	—	—	0.00%	0.01%	0.00%
Yb_2O_3	—	—	—	—	0.01%
ZnO	1.73%	0.09%	1.79%	0.08%	0.08%
ZrO_2	3.50%	0.15%	0.00%	5.30%	5.45%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%

(a) Compositional values are rounded to 2 decimal places.
(b) — indicates empty data field.
(c) Boldface indicates target values are used for B_2O_3 and Li_2O, which were not measured by XRF.

Table 4.1. Compositional Analysis (wt%) of HLW Algorithm Glasses by XRF[(a)] (continued).

Oxides	HLW-ALG-21	HLW-ALG-22	HLW-ALG-23	HLW-ALG-24	HLW-ALG-25
Ag_2O	0.21%	0.19%	0.19%	0.14%	0.07%
Al_2O_3	3.23%	3.38%	3.28%	13.15%	3.08%
As_2O_5	—[(b)]	—	—	—	0.00%
Au	—	—	—	—	—
B_2O_3	**4.81%**[(c)]	**6.60%**	**4.81%**	**4.81%**	**10.10%**
BaO	0.05%	0.06%	0.05%	—	0.04%
Bi_2O_3	—	—	—	0.05%	—
CaO	0.73%	0.69%	0.66%	1.02%	0.37%
CdO	0.14%	0.14%	0.12%	0.06%	—
Ce_2O_3	0.07%	0.07%	0.08%	0.14%	0.06%
Cl	—	—	—	0.02%	—
CoO	0.01%	0.00%	—	—	—
Cr_2O_3	0.63%	0.60%	0.58%	—	0.62%
Cs_2O	—	—	—	0.04%	—
CuO	0.05%	0.07%	0.07%	0.07%	0.02%
Er_2O_3	—	0.01%	0.02%	—	0.02%
Eu_2O_3	—	—	—	—	0.02%
Fe_2O_3	10.03%	9.64%	9.28%	1.94%	11.26%
Gd_2O_3	—	—	—	—	—
GeO_2	—	—	—	—	—
HfO_2	0.25%	0.25%	0.24%	0.22%	—
HgO	—	—	—	—	—
Ho_2O_3	—	—	—	—	—
IrO_2	—	—	—	—	—
K_2O	0.26%	0.28%	0.26%	0.48%	0.26%
La_2O_3	0.15%	0.16%	0.09%	0.12%	0.06%
Li_2O	**2.48%**	**2.41%**	**2.07%**	**4.27%**	**2.02%**
MgO	0.07%	0.10%	—	0.22%	0.12%
MnO	1.32%	1.29%	1.22%	3.28%	7.19%
MoO_3	0.04%	—	—	0.05%	—
Na_2O	16.26%	15.32%	17.96%	9.55%	17.11%
Nd_2O_3	0.14%	0.13%	0.12%	0.27%	0.10%
NiO	0.57%	0.56%	0.55%	0.06%	1.00%
P_2O_5	0.15%	0.17%	0.14%	0.32%	0.14%
PbO	0.19%	0.19%	0.17%	0.56%	0.19%
PdO	—	—	—	—	—
Pr_2O_3	—	—	—	0.07%	—
Rb_2O	0.02%	0.03%	0.03%	—	—
Re_2O_7	—	—	—	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	—	—	—	0.10%	0.02%
SO_3	0.19%	0.19%	0.19%	0.14%	0.20%
SeO_2	0.01%	0.01%	0.01%	0.00%	—
SiO_2	37.90%	37.42%	38.52%	36.25%	45.31%
Sm_2O_3	—	—	—	—	0.02%
SnO_2	0.02%	0.01%	0.01%	—	0.02%
SrO	0.03%	0.02%	0.02%	3.91%	0.03%
Tb_4O_7	—	—	—	—	0.02%
ThO_2	5.56%	5.96%	5.71%	5.03%	0.21%
TiO_2	0.06%	0.06%	0.03%	—	0.06%
UO_3	4.73%	4.65%	4.50%	5.30%	0.01%
WO_3	0.15%	0.14%	0.14%	0.07%	—
Y_2O_3	0.02%	0.02%	0.02%	—	0.00%
Yb_2O_3	—	—	—	—	—
ZnO	0.12%	0.13%	0.12%	0.10%	0.07%
ZrO_2	9.35%	9.03%	8.70%	8.08%	0.17%
TOTAL	100.0%	100.0%	100.0%	99.9%	100.0%

(a) Compositional values are rounded to 2 decimal places.
(b) — indicates empty data field.
(c) Boldface indicates target values are used for B_2O_3 and Li_2O, which were not measured by XRF.

Table 4.1. Compositional Analysis (wt%) of HLW Algorithm Glasses by XRF[(a)] (continued).

Oxides	HLW-ALG-26	HLW-ALG-27	HLW-ALG-28	HLW-ALG-29	HLW-ALG-30
Ag_2O	0.11%	0.06%	0.07%	0.08%	0.05%
Al_2O_3	5.31%	13.10%	9.08%	10.13%	7.92%
As_2O_5	—[(b)]	0.00%	—	—	—
Au	—	—	—	—	—
B_2O_3	**7.47%**[(c)]	**14.03%**	**14.03%**	**14.03%**	**9.60%**
BaO	—	0.05%	0.04%	0.05%	0.09%
Bi_2O_3	—	—	—	—	—
CaO	0.74%	0.43%	0.42%	0.47%	0.45%
CdO	—	—	—	—	0.67%
Ce_2O_3	0.13%	0.08%	0.07%	0.09%	0.27%
Cl	—	—	—	—	0.05%
CoO	—	0.01%	0.01%	0.00%	—
Cr_2O_3	—	0.01%	0.39%	0.42%	0.18%
Cs_2O	0.05%	—	—	—	—
CuO	0.06%	0.00%	0.00%	0.00%	0.06%
Er_2O_3	—	0.01%	0.02%	0.01%	0.01%
Eu_2O_3	—	—	—	—	—
Fe_2O_3	5.45%	11.76%	12.40%	8.57%	10.34%
Gd_2O_3	—	—	—	—	0.01%
GeO_2	—	—	—	0.00%	—
HfO_2	0.20%	—	—	0.20%	0.08%
HgO	—	—	—	—	—
Ho_2O_3	—	—	—	—	—
IrO_2	—	0.01%	—	—	—
K_2O	0.37%	0.22%	0.22%	0.24%	0.26%
La_2O_3	—	0.08%	0.07%	0.08%	0.17%
Li_2O	**3.02%**	**1.93%**	**1.93%**	**1.93%**	**3.10%**
MgO	0.16%	0.11%	—	0.12%	0.11%
MnO	2.45%	0.02%	2.41%	—	0.33%
MoO_3	—	—	—	—	—
Na_2O	8.91%	17.68%	17.90%	17.91%	14.84%
Nd_2O_3	0.22%	0.13%	0.14%	0.16%	0.23%
NiO	0.05%	0.00%	0.59%	0.64%	0.46%
P_2O_5	0.25%	0.16%	0.17%	0.17%	0.47%
PbO	0.43%	0.24%	0.23%	0.26%	0.08%
PdO	—	—	—	—	0.05%
Pr_2O_3	0.06%	—	—	—	—
Rb_2O	—	—	—	—	—
Re_2O_7	—	—	—	—	—
Rh_2O_3	—	—	—	—	—
RuO_2	0.03%	0.04%	0.03%	0.04%	0.08%
SO_3	0.12%	0.20%	0.23%	0.15%	0.13%
SeO_2	0.00%	—	—	0.01%	0.01%
SiO_2	41.83%	37.06%	39.36%	36.64%	45.00%
Sm_2O_3	—	0.02%	—	—	—
SnO_2	0.01%	0.02%	0.02%	0.01%	0.02%
SrO	4.80%	0.04%	0.02%	0.02%	0.16%
Tb_4O_7	—	0.01%	—	0.01%	0.02%
ThO_2	4.27%	—	—	—	—
TiO_2	—	0.01%	0.01%	—	—
UO_3	4.83%	—	—	—	0.87%
WO_3	—	—	—	—	—
Y_2O_3	—	0.00%	0.00%	—	0.00%
Yb_2O_3	—	—	—	—	—
ZnO	1.52%	2.42%	0.08%	0.08%	0.66%
ZrO_2	7.08%	0.02%	0.00%	7.44%	3.17%
TOTAL	99.9%	100.0%	99.9%	100.0%	100.0%

[(a)] Compositional values are rounded to 2 decimal places.
[(b)] — indicates empty data field.
[(c)] Boldface indicates target values are used for B_2O_3 and Li_2O, which were not measured by XRF.

Table 4.1. Compositional Analysis (wt%) of HLW Algorithm Glasses by XRF[(a)] (continued).

Oxides	HLW-ALG-31	HLW-ALG-32	HLW-ALG-33	HLW-ALG-34	HLW-ALG-35
Ag_2O	0.06%	0.10%	0.09%	0.06%	0.06%
Al_2O_3	2.59%	6.35%	12.07%	3.18%	6.26%
As_2O_5	—[(b)]	—	—	—	—
Au	—	0.01%	—	—	—
B_2O_3	**10.88%**[(c)]	**4.81%**	**8.01%**	**8.22%**	**4.81%**
BaO	0.04%	—	0.06%	0.04%	—
Bi_2O_3	—	—	—	—	—
CaO	0.39%	0.59%	0.55%	0.38%	0.61%
CdO	—	1.33%	—	—	0.08%
Ce_2O_3	0.05%	0.08%	0.10%	0.05%	0.16%
Cl	—	—	—	—	0.04%
CoO	0.01%	0.01%	0.01%	—	0.01%
Cr_2O_3	0.61%	0.49%	0.49%	0.62%	0.27%
Cs_2O	—	—	—	—	—
CuO	—	—	—	—	0.01%
Er_2O_3	0.01%	0.01%	0.01%	0.02%	0.02%
Eu_2O_3	—	0.02%	—	0.02%	—
Fe_2O_3	12.02%	11.93%	10.79%	12.17%	13.57%
Gd_2O_3	—	—	—	—	—
GeO_2	—	—	0.00%	—	0.01%
HfO_2	0.13%	—	0.18%	—	0.06%
HgO	—	0.01%	—	—	—
Ho_2O_3	—	—	—	—	—
IrO_2	—	—	—	—	—
K_2O	0.21%	0.27%	0.28%	0.23%	0.50%
La_2O_3	0.05%	0.18%	0.09%	0.07%	0.33%
Li_2O	**3.08%**	**3.97%**	**3.78%**	**2.02%**	**2.80%**
MgO	0.13%	0.15%	0.11%	0.11%	0.43%
MnO	2.12%	7.07%	0.00%	7.23%	4.05%
MoO_3	0.01%	—	0.01%	—	—
Na_2O	12.15%	9.82%	18.38%	19.26%	10.17%
Nd_2O_3	0.10%	0.15%	0.15%	0.10%	0.38%
NiO	0.98%	0.73%	0.71%	1.02%	0.19%
P_2O_5	0.17%	0.22%	0.20%	0.16%	0.26%
PbO	0.19%	0.32%	0.30%	0.20%	0.41%
PdO	—	—	—	—	—
Pr_2O_3	—	0.06%	0.03%	—	0.05%
Rb_2O	0.00%	—	—	—	—
Re_2O_7	—	0.02%	—	—	0.01%
Rh_2O_3	—	—	—	—	—
RuO_2	0.02%	0.05%	0.04%	0.02%	—
SO_3	0.20%	0.24%	0.22%	0.22%	0.38%
SeO_2	0.00%	—	—	—	—
SiO_2	46.92%	40.54%	36.18%	44.19%	40.61%
Sm_2O_3	—	—	—	0.03%	—
SnO_2	0.02%	0.02%	0.02%	0.02%	0.03%
SrO	0.02%	9.71%	0.02%	0.02%	7.48%
Tb_4O_7	—	0.01%	0.01%	0.03%	—
ThO_2	—	—	—	—	0.57%
TiO_2	0.07%	0.11%	0.02%	0.08%	—
UO_3	—	—	—	—	1.42%
WO_3	—	—	—	—	—
Y_2O_3	—	—	0.01%	—	—
Yb_2O_3	—	—	—	0.01%	—
ZnO	1.69%	0.43%	0.09%	0.07%	1.29%
ZrO_2	5.07%	—	6.99%	0.16%	2.54%
TOTAL	100.0%	99.8%	100.0%	100.0%	99.9%

(a) Compositional values are rounded to 2 decimal places.
(b) — indicates empty data field.
(c) Boldface indicates target values are used for B_2O_3 and Li_2O, which were not measured by XRF.

Table 4.1. Compositional Analysis (wt%) of HLW Algorithm Glasses by XRF[(a)] (continued).

Oxides	HLW-ALG-36	HLW-ALG-37	HLW-ALG-38	HLW-ALG-39	HLW-ALG-40
Ag_2O	0.12%	0.16%	0.19%	0.13%	0.08%
Al_2O_3	7.00%	6.73%	3.95%	3.15%	9.60%
As_2O_5	—[(b)]	—	—	—	—
Au	—	—	—	—	—
B_2O_3	**6.51%**[(c)]	**4.81%**	**7.90%**	**10.20%**	**8.44%**
BaO	—	—	0.06%	0.05%	0.09%
Bi_2O_3	—	0.04%	—	—	—
CaO	0.73%	0.99%	0.70%	0.50%	0.58%
CdO	0.49%	0.06%	0.13%	0.09%	0.80%
Ce_2O_3	0.14%	0.17%	0.08%	—	0.35%
Cl	—	0.01%	—	—	0.08%
CoO	0.01%	—	—	0.01%	0.01%
Cr_2O_3	0.38%	—	0.58%	0.43%	0.22%
Cs_2O	0.03%	0.03%	—	—	—
CuO	0.05%	0.06%	0.05%	—	0.06%
Er_2O_3	0.03%	—	0.01%	0.01%	0.01%
Eu_2O_3	—	—	—	—	—
Fe_2O_3	13.40%	7.22%	9.21%	6.77%	13.31%
Gd_2O_3	—	—	—	—	—
GeO_2	—	—	—	—	—
HfO_2	0.07%	0.24%	0.23%	0.17%	0.10%
HgO	—	—	—	—	—
Ho_2O_3	—	—	—	—	—
IrO_2	—	—	—	—	—
K_2O	0.35%	0.45%	0.26%	0.25%	0.27%
La_2O_3	—	—	0.14%	0.08%	0.26%
Li_2O	**2.90%**	**2.58%**	**2.88%**	**3.11%**	**3.05%**
MgO	0.19%	0.24%	0.12%	0.06%	0.11%
MnO	2.32%	3.24%	1.22%	0.90%	0.42%
MoO_3	—	—	0.03%	0.03%	—
Na_2O	12.43%	9.09%	10.90%	10.97%	14.58%
Nd_2O_3	0.21%	0.28%	0.12%	0.07%	0.30%
NiO	0.89%	0.08%	0.52%	0.37%	0.59%
P_2O_5	0.25%	0.33%	0.18%	0.16%	0.60%
PbO	0.41%	0.56%	0.18%	0.13%	0.09%
PdO	—	—	—	—	0.04%
Pr_2O_3	0.06%	0.07%	—	—	—
Rb_2O	—	—	0.02%	—	—
Re_2O_7	—	—	—	—	—
Rh_2O_3	—	—	—	—	0.03%
RuO_2	0.03%	0.11%	—	—	0.11%
SO_3	0.26%	0.19%	0.21%	0.14%	0.18%
SeO_2	—	—	0.01%	0.00%	0.00%
SiO_2	37.46%	34.90%	41.16%	47.04%	39.98%
Sm_2O_3	—	—	—	—	—
SnO_2	0.02%	0.01%	0.01%	0.01%	0.02%
SrO	6.77%	6.19%	0.03%	0.03%	0.20%
Tb_4O_7	—	—	—	—	0.01%
ThO_2	1.77%	5.26%	5.54%	4.02%	0.01%
TiO_2	—	—	0.08%	0.02%	—
UO_3	1.89%	6.20%	4.50%	3.33%	1.16%
WO_3	—	0.06%	0.14%	0.10%	—
Y_2O_3	—	—	0.01%	—	0.00%
Yb_2O_3	—	—	—	—	—
ZnO	0.11%	0.91%	0.44%	1.58%	0.21%
ZrO_2	2.62%	8.64%	8.20%	6.08%	4.05%
TOTAL	99.9%	99.9%	100.0%	100.0%	100.0%

(a) Compositional values are rounded to 2 decimal places.
(b) — indicates empty data field.
(c) Boldface indicates target values are used for B_2O_3 and Li_2O, which were not measured by XRF.

Table 4.2. PCT Release Data (Leachate Concentration in ppm and Normalized Release in g/l) for the HLW Algorithm Glasses.

Glass ID	PCT-B (ppm)	PCT-Li (ppm)	PCT-Na (ppm)	PCT-B (g/l)	PCT-Li (g/l)	PCT-Na (g/l)	Leachate pH
HLW-ALG-01	40.76	11.37	115.30	1.24	0.74	0.90	11.08
HLW-ALG-02	24.75	9.54	70.73	0.72	0.58	0.62	10.78
HLW-ALG-03	586.30	151.60	1663.00	21.90	10.68	11.82	12.18
HLW-ALG-04	305.60	82.35	678.80	8.84	6.16	5.73	10.87
HLW-ALG-05	52.34	65.41	212.30	3.50	3.29	3.20	11.62
HLW-ALG-06	15.44	11.73	144.80	1.03	1.00	1.25	11.55
HLW-ALG-07	11.50	5.80	32.58	0.35	0.38	0.37	10.66
HLW-ALG-08	13.86	7.93	99.08	0.93	0.82	0.96	11.33
HLW-ALG-09	22.25	11.25	149.90	1.49	1.22	1.34	11.45
HLW-ALG-10	365.10	62.06	1006.00	12.44	6.62	7.79	11.53
HLW-ALG-11	14.66	13.44	17.56	0.39	0.48	0.39	10.55
HLW-ALG-12	15.23	10.18	124.90	1.02	0.80	1.06	11.45
HLW-ALG-13	1.78	9.53	45.65	0.12	0.61	0.65	11.06
HLW-ALG-14	5.73	24.60	28.71	0.38	0.88	0.81	10.97
HLW-ALG-15	63.32	7.71	144.80	1.45	0.86	1.11	10.54
HLW-ALG-16	97.74	13.02	196.60	2.27	1.39	1.52	10.55
HLW-ALG-17	412.90	60.28	1155.00	12.86	6.42	8.94	11.43
HLW-ALG-18	22.12	8.98	62.78	0.64	0.56	0.57	10.53
HLW-ALG-19	86.26	24.40	217.20	2.88	1.98	1.81	11.02
HLW-ALG-20	133.90	47.36	416.70	5.56	3.48	3.23	11.61
HLW-ALG-21	12.20	6.75	157.20	0.82	0.59	1.20	11.54
HLW-ALG-22	18.60	6.84	126.80	0.91	0.61	1.03	11.43
HLW-ALG-23	15.59	5.50	193.70	1.04	0.57	1.35	11.65
HLW-ALG-24	5.02	11.19	42.03	0.34	0.56	0.58	10.98
HLW-ALG-25	373.10	63.36	967.40	11.90	6.75	7.49	11.41
HLW-ALG-26	0.17	6.02	28.03	0.01	0.43	0.39	10.53
HLW-ALG-27	84.16	11.78	141.40	1.93	1.32	1.08	10.47
HLW-ALG-28	101.50	14.36	177.50	2.33	1.60	1.36	10.67
HLW-ALG-29	46.97	5.68	99.16	1.08	0.63	0.76	10.48
HLW-ALG-30	9.78	6.14	61.71	0.33	0.43	0.54	10.67
HLW-ALG-31	53.31	17.82	91.65	1.58	1.25	1.05	10.18
HLW-ALG-32	6.57	11.55	43.68	0.44	0.63	0.63	11.01
HLW-ALG-33	15.75	8.59	113.60	0.63	0.49	0.87	11.27
HLW-ALG-34	361.20	65.55	1208.00	14.15	6.99	8.57	11.59
HLW-ALG-35	5.81	9.26	61.32	0.39	0.71	0.76	11.02
HLW-ALG-36	18.93	14.54	107.20	0.94	1.08	1.15	11.30
HLW-ALG-37	2.68	6.50	36.41	0.18	0.54	0.52	10.88
HLW-ALG-38	9.50	1.89	26.19	0.39	0.14	0.33	9.79
HLW-ALG-39	22.19	10.88	43.68	0.70	0.75	0.53	10.18
HLW-ALG-40	9.54	8.18	66.10	0.36	0.58	0.62	10.85

Table 4.3. Summary of Measured Properties for the HLW Algorithm Glasses.

	Constraint Limits	HLW-ALG-01	HLW-ALG-02	HLW-ALG-03	HLW-ALG-04	HLW-ALG-05
r_B (g/l)	16.7	1.243	0.719	**21.903**[a]	8.839	3.505
r_{Na} (g/l)	13.3	0.899	0.622	11.819	5.726	3.202
r_{Li} (g/l)	9.6	0.735	0.578	**10.675**	6.164	3.285
$T_{1\%}$ (ºC)	950	ND[b]	ND	758.9	ND	949.2
η_{1150}	20-80	29.55	37.88	**17.26**	29.46	**15.74**
η_{1100}	10-150	43.08	59.04	25.75	42.72	23.18
ε_{1100}	0.2-0.7	0.489	0.396	0.572	0.408	0.276
ε_{1200}	0.2-0.7	0.650	0.519	**0.760**	0.532	0.402
Outside Phase 1 Modeling Compositional Range?		Yes	Yes	Yes	Yes	No
Major Crystalline Phase at $T_{1\%}$		Spinel	Spinel	Spinel	Spinel	Spinel

	Constraint Limits	HLW-ALG-06	HLW-ALG-07	HLW-ALG-08	HLW-ALG-09	HLW-ALG-10
r_B (g/l)	16.7	1.034	0.346	0.929	1.490	12.445
r_{Na} (g/l)	13.3	1.248	0.373	0.958	1.337	7.788
r_{Li} (g/l)	9.6	0.998	0.383	0.820	1.219	6.615
$T_{1\%}$ (ºC)	950	**955.1**	ND	**1170.5**	800.8	775.0
η_{1150}	20-80	30.35	63.92	23.46	20.30	**19.30**
η_{1100}	10-150	46.36	105.29	41.28	31.29	28.21
ε_{1100}	0.2-0.7	0.385	0.259	0.316	0.386	0.518
ε_{1200}	0.2-0.7	0.520	0.368	0.452	0.574	**0.729**
Outside Phase 1 Modeling Compositional Range?		Yes	No	No	Yes	Yes
Major Crystalline Phase at $T_{1\%}$		Spinel	RuO_2 (Trace)	ZrO_2	Spinel	Spinel

[a] Highlighted values do not meet the constraint limit.
[b] ND = Not determined.

Table 4.3. Summary of Measured Properties for the HLW Algorithm Glasses (continued).

	Constraint Limits	HLW-ALG-11	HLW-ALG-12	HLW-ALG-13	HLW-ALG-14	HLW-ALG-15
r_B (g/l)	16.7	0.387	1.020	0.119	0.384	1.454
r_{Na} (g/l)	13.3	0.390	1.059	0.647	0.806	1.110
r_{Li} (g/l)	9.6	0.481	0.797	0.612	0.881	0.861
$T_{1\%}$ (ºC)	950	**1181.8**[(a)]	880.3	**1293.2**	**991.7**	797.4
η_{1150}	20-80	27.23	24.45	42.4[(c)]	**18.73**	33.82
η_{1100}	10-150	44.09	38.84	ND	27.78	53.81
ε_{1100}	0.2-0.7	0.370	0.460	0.298	0.350	0.455
ε_{1200}	0.2-0.7	0.487	0.596	0.438	0.515	0.613
Outside Phase 1 Modeling Compositional Range?		Yes	Yes	No	No	Yes
Major Crystalline Phase at $T_{1\%}$		ZrO_2/ThO_2	Spinel	ZrO_2/ThO_2	Spinel	Spinel

	Constraint Limits	HLW-ALG-16	HLW-ALG-17	HLW-ALG-18	HLW-ALG-19	HLW-ALG-20
r_B (g/l)	16.7	2.273	12.863	0.641	2.878	5.562
r_{Na} (g/l)	13.3	1.522	8.940	0.571	1.815	3.228
r_{Li} (g/l)	9.6	1.387	6.424	0.563	1.976	3.485
$T_{1\%}$ (ºC)	950	ND[(b)]	819.7	635.7	750.0	637.9
η_{1150}	20-80	43.3	**18.98**	61.92	32.34	26.3
η_{1100}	10-150	68.52	26.82	92.32	50.4	40.2
ε_{1100}	0.2-0.7	0.477	0.391	0.372	0.408	0.532
ε_{1200}	0.2-0.7	0.682	0.543	0.512	0.560	**0.732**
Outside Phase 1 Modeling Compositional Range?		Yes	Yes	No	Yes	Yes
Major Crystalline Phase at $T_{1\%}$		Spinel	Spinel/NaMnFe Silicate	Spinel	Spinel	Spinel

[(a)] Highlighted values do not meet the constraint limit.
[(b)] ND = Not determined.
[(c)] Fitting not performed. Measured value at 1154ºC used.

Table 4.3. Summary of Measured Properties for the HLW Algorithm Glasses (continued).

	Constraint Limits	HLW-ALG-21	HLW-ALG-22	HLW-ALG-23	HLW-ALG-24	HLW-ALG-25
r_B (g/l)	16.7	0.817	0.908	1.044	0.336	11.902
r_{Na} (g/l)	13.3	1.202	1.029	1.353	0.577	7.488
r_{Li} (g/l)	9.6	0.587	0.612	0.573	0.565	6.752
$T_{1\%}$ (ºC)	950	**1129.4**[(a)]	**995.9**	**1023.6**	**1277.8**	773.5
η_{1150}	20-80	37.3	32.55	33.75	ND	**17.69**
η_{1100}	10-150	68.31	54.86	57.31	ND	25.79
ε_{1100}	0.2-0.7	0.477	0.546	**0.731**	0.336	0.452
ε_{1200}	0.2-0.7	0.613	**0.742**	**0.928**	0.442	0.585
Outside Phase 1 Modeling Compositional Range?		Yes	Yes	Yes	Yes	Yes
Major Crystalline Phase at $T_{1\%}$		ZrO_2/ThO_2	ZrO_2/ThO_2	$Na_2ZrSi_2O_7/ZrO_2$	ZrO_2/ThO_2	Spinel

	Constraint Limits	HLW-ALG-26	HLW-ALG-27	HLW-ALG-28	HLW-ALG-29	HLW-ALG-30
r_B (g/l)	16.7	0.007	1.932	2.331	1.078	0.328
r_{Na} (g/l)	13.3	0.393	1.084	1.360	0.760	0.543
r_{Li} (g/l)	9.6	0.429	1.316	1.604	0.634	0.427
$T_{1\%}$ (ºC)	950	ND[(b)]	800.1	855.8	ND	730.8
η_{1150}	20-80	63.43	33.42	22.53	38.79	40.18
η_{1100}	10-150	107.17	49.82	33.13	62.64	61.64
ε_{1100}	0.2-0.7	0.250	0.491	0.448	0.441	0.458
ε_{1200}	0.2-0.7	0.374	0.664	0.599	0.620	0.609
Outside Phase 1 Modeling Compositional Range?		No	Yes	Yes	Yes	Yes
Major Crystalline Phase at $T_{1\%}$		ThO_2	Spinel/NaAlFe Silicate	Spinel	Spinel	Spinel

(a) Highlighted values do not meet the constraint limit.
(b) ND = Not determined.

Table 4.3. Summary of Measured Properties for the HLW Algorithm Glasses (continued).

	Constraint Limits	HLW-ALG-31	HLW-ALG-32	HLW-ALG-33	HLW-ALG-34	HLW-ALG-35
r_B (g/l)	16.7	1.577	0.440	0.634	14.147	0.389
r_{Na} (g/l)	13.3	1.055	0.632	0.867	8.569	0.764
r_{Li} (g/l)	9.6	1.246	0.626	0.489	6.986	0.712
$T_{1\%}$ (ºC)	1075	1003.7	**1124.8**[(a)]	**1133.5**	824.6	998.5
η_{1150}	20-80	40.2	**15.81**	32.56	**15.14**	31.68
η_{1100}	10-150	64.36	24.1	50.23	22.09	50.49
ε_{1100}	0.2-0.7	0.253	0.330	0.549	0.520	0.266
ε_{1200}	0.2-0.7	0.376	0.495	**0.729**	**0.720**	0.393
Outside Phase 1 Modeling Compositional Range?		No	No	Yes	Yes	No
Major Crystalline Phase at $T_{1\%}$		Spinel	Spinel	ZrO_2/Spinel	Spinel	Spinel

	Constraint Limits	HLW-ALG-36	HLW-ALG-37	HLW-ALG-38	HLW-ALG-39	HLW-ALG-40
r_B (g/l)	16.7	0.936	0.180	0.387	0.700	0.364
r_{Na} (g/l)	13.3	1.153	0.524	0.332	0.533	0.621
r_{Li} (g/l)	9.6	1.078	0.542	0.141	0.753	0.577
$T_{1\%}$ (ºC)	1075	1029.7	**1510.9**	**1138.7**	ND	1012.4
η_{1150}	20-80	22.63	67.88	50.28[(c)]	65.13	42.26
η_{1100}	10-150	35.5	123.89	ND[(b)]	106.54	64.78
ε_{1100}	0.2-0.7	0.392	0.255	0.204	0.278	0.450
ε_{1200}	0.2-0.7	0.573	0.362	0.298	0.392	0.598
Outside Phase 1 Modeling Compositional Range?		No	No	No	No	Yes
Major Crystalline Phase at $T_{1\%}$		Spinel	ZrO_2/ThO_2	ZrO_2/ThO_2/Spinel	Spinel	Spinel

(a) Highlighted values do not meet the constraint limit.
(b) ND = Not determined.
(c) Fitting not performed. Measured value at 1154ºC used.

Table 4.4. Measured and Fitted Viscosity Data for HLW Algorithm Glasses.

Glass ID	Measured Viscosity		Fitted Viscosity	
	Temperature (°C)	Viscosity (P)	Temperature (°C)	Viscosity (P)
HLW-ALG-01	959	167.81	1000	106.78
	1057	60.84	1050	65.89
	1156	28.96	1100	43.08
	1253	15.18	1150	29.55
HLW-ALG-02	959	289.17	1000	171.28
	1059	88.47	1050	97.27
	1160	34.87	1100	59.04
	1259	16.77	1150	37.88
HLW-ALG-03	960	108.34	1000	67.84
	1061	36.31	1050	40.48
	1161	16.08	1100	25.75
	1261	8.18	1150	17.26
HLW-ALG-04	958	170.17	1000	106.22
	1060	59.35	1050	65.25
	1161	27.49	1100	42.72
	1262	14.78	1150	29.46
HLW-ALG-05	958	97.28	1000	59.66
	1058	33.06	1050	35.99
	1159	14.95	1100	23.18
	1258	7.82	1150	15.74
HLW-ALG-06	964	198.59	1000	128.14
	1067	62.52	1050	74.67
	1170	26.24	1100	46.36
	1273	12.71	1150	30.35
HLW-ALG-07	959	639.26	1000	352.67
	1058	172.10	1050	185.18
	1156	58.72	1100	105.29
	1255	26.85	1150	63.92
HLW-ALG-08	970	273.63	1000	165.77
	1065	64.77	1050	78.71
	1159	21.24	1100	41.28
	1254	8.86	1150	23.46
HLW-ALG-09	963	157.46	1000	93.65
	1057	46.56	1050	51.75
	1153	20.60	1100	31.29
	1249	9.94	1150	20.30
HLW-ALG-10	971	95.80	1000	70.16
	1070	36.23	1050	43.24
	1168	17.00	1100	28.21
	1267	9.19	1150	19.30

Table 4.4. Measured and Fitted Viscosity Data for HLW Algorithm Glasses (continued).

Glass ID	Measured Viscosity		Fitted Viscosity	
	Temperature (°C)	Viscosity (P)	Temperature (°C)	Viscosity (P)
HLW-ALG-11	973	212.31	1000	144.35
	1073	59.33	1050	76.47
	1172	21.96	1100	44.09
	1272	10.60	1150	27.23
HLW-ALG-12	984	172.35	1000	133.49
	1071	52.12	1050	67.70
	1160	22.81	1100	38.84
	1249	11.84	1150	24.45
HLW-ALG-13	966	See note[a]	No fitting performed	
	1059	See note[a]		
	1154	42.40		
	1249	18.47		
HLW-ALG-14	952	121.57	1000	70.89
	1055	40.99	1050	43.17
	1158	17.78	1100	27.78
	1261	8.88	1150	18.73
HLW-ALG-15	955	293.00	1000	162.09
	1054	86.45	1050	90.41
	1153	32.97	1100	53.81
	1251	15.15	1150	33.82
HLW-ALG-16	956	366.30	1000	205.26
	1053	110.76	1050	114.70
	1151	43.02	1100	68.52
	1248	20.05	1150	43.30
HLW-ALG-17	963	95.36	1000	63.83
	1063	35.68	1050	40.00
	1163	17.57	1100	26.82
	1264	10.02	1150	18.98
HLW-ALG-18	959	368.15	1000	235.26
	1060	131.16	1050	143.69
	1161	57.01	1100	92.32
	1263	28.57	1150	61.92
HLW-ALG-19	959	244.87	1000	145.51
	1061	73.46	1050	82.92
	1164	29.04	1100	50.40
	1265	13.67	1150	32.34
HLW-ALG-20	956	192.43	1000	111.63
	1058	59.48	1050	64.84
	1160	24.48	1100	40.20
	1262	11.83	1150	26.30

[a] Crystallization suspected.

Table 4.4. Measured and Fitted Viscosity Data for HLW Algorithm Glasses (continued).

Glass ID	Measured Viscosity		Fitted Viscosity	
	Temperature (°C)	Viscosity (P)	Temperature (°C)	Viscosity (P)
HLW-ALG-21	978	508.70	1000	329.57
	1066	109.65	1050	139.69
	1156	34.93	1100	68.31
	1246	14.63	1150	37.30
HLW-ALG-22	981	251.52	1000	192.67
	1074	77.13	1050	98.80
	1169	25.65	1100	54.86
	1264	12.29	1150	32.55
HLW-ALG-23	973	316.45	1000	208.79
	1073	78.53	1050	104.65
	1173	27.14	1100	57.31
	1273	11.58	1150	33.75
HLW-ALG-24	Highly non-newtonain behavior observed			
HLW-ALG-25	972	85.72	1000	63.77
	1072	32.69	1050	39.42
	1171	15.24	1100	25.79
	1271	8.27	1150	17.69
HLW-ALG-26	963	741.02	1000	403.18
	1057	185.41	1050	197.06
	1155	58.10	1100	107.17
	1252	26.97	1150	63.43
HLW-ALG-27[a]	958	193.88	1000	124.46
	1060	69.76	1050	77.08
	1163	30.56	1100	49.82
	1264	15.05	1150	33.42
HLW-ALG-28	960	125.21	1000	81.83
	1061	45.60	1050	50.80
	1163	20.77	1100	33.13
	1263	10.63	1150	22.53
HLW-ALG-29	957	346.36	1000	194.28
	1059	96.19	1050	106.82
	1161	35.07	1100	62.64
	1262	15.59	1150	38.79
HLW-ALG-30	960	293.76	1000	176.18
	1053	98.39	1050	100.42
	1148	40.42	1100	61.64
	1243	20.63	1150	40.18

[a] Apparent phase separation observed.

Table 4.4. Measured and Fitted Viscosity Data for HLW Algorithm Glasses (continued).

Glass ID	Measured Viscosity		Fitted Viscosity	
	Temperature (°C)	Viscosity (P)	Temperature (°C)	Viscosity (P)
HLW-ALG-31	960	350.08	1000	201.85
	1060	98.75	1050	109.71
	1159	37.08	1100	64.36
	1260	16.93	1150	40.20
HLW-ALG-32	948	127.33	1000	66.62
	1046	40.33	1050	38.79
	1144	16.62	1100	24.10
	1243	8.10	1150	15.81
HLW-ALG-33	951	273.94	1000	145.15
	1050	83.43	1050	82.30
	1149	33.05	1100	50.23
	1249	15.69	1150	32.56
HLW-ALG-34	952	88.98	1000	53.66
	1046	34.55	1050	33.60
	1141	16.30	1100	22.09
	1236	8.54	1150	15.14
HLW-ALG-35	972	234.45	1000	158.98
	1068	70.12	1050	86.00
	1166	27.74	1100	50.49
	1264	13.23	1150	31.68
HLW-ALG-36	969	167.31	1000	109.39
	1065	51.03	1050	59.68
	1163	20.33	1100	35.50
	1261	10.01	1150	22.63
HLW-ALG-37	975	760.01	1000	511.62
	1067	200.99	1050	241.94
	1161	56.29	1100	123.89
	1255	23.55	1150	67.88
HLW-ALG-38	964	See note[a]	No fitting performed	
	1059	160.64		
	1154	50.28		
	1249	21.62		
HLW-ALG-39	968	632.48	1000	378.63
	1064	159.64	1050	189.98
	1162	59.39	1100	106.54
	1260	27.26	1150	65.13
HLW-ALG-40	951	369.89	1000	189.83
	1052	107.47	1050	106.26
	1155	38.86	1100	64.78
	1258	20.38	1150	42.26

[a] Strongly non-newtonian behavior at 964 °C.

Table 4.5. Measured and Fitted Electrical Conductivity Data for HLW Algorithm Glasses.

Glass ID	Measured Electrical Conductivity		Fitted Electrical Conductivity	
	Temperature (°C)	Conductivity (S/cm)	Temperature (°C)	Conductivity (S/cm)
HLW-ALG-01	975	0.317	1050	0.417
	1069	0.444	1100	0.489
	1162	0.587	1150	0.567
	1261	0.756	1200	0.650
HLW-ALG-02	969	0.236	1050	0.334
	1062	0.349	1100	0.396
	1154	0.463	1150	0.458
	1254	0.584	1200	0.519
HLW-ALG-03	970	0.344	1050	0.481
	1062	0.491	1100	0.572
	1155	0.694	1150	0.665
	1248	0.841	1200	0.760
HLW-ALG-04	967	0.229	1050	0.342
	1059	0.345	1100	0.408
	1150	0.501	1150	0.472
	1248	0.568	1200	0.532
HLW-ALG-05	983	0.153	1050	0.220
	1080	0.250	1100	0.276
	1174	0.374	1150	0.337
	1270	0.494	1200	0.402
HLW-ALG-06	937	0.189	1050	0.320
	1036	0.298	1100	0.385
	1132	0.436	1150	0.452
	1229	0.555	1200	0.520
HLW-ALG-07	927	0.113	1050	0.211
	1031	0.195	1100	0.259
	1128	0.288	1150	0.311
	1223	0.394	1200	0.368
HLW-ALG-08	943	0.141	1050	0.254
	1041	0.243	1100	0.316
	1139	0.371	1150	0.382
	1236	0.501	1200	0.452
HLW-ALG-09	946	0.187	1050	0.309
	1042	0.294	1100	0.386
	1137	0.439	1150	0.474
	1231	0.657	1200	0.574
HLW-ALG-10	946	0.273	1050	0.427
	1043	0.395	1100	0.518
	1142	0.627	1150	0.619
	1230	0.791	1200	0.729

Table 4.5. Measured and Fitted Electrical Conductivity Data for HLW Algorithm Glasses (continued).

Glass ID	Measured Electrical Conductivity		Fitted Electrical Conductivity	
	Temperature (°C)	Conductivity (S/cm)	Temperature (°C)	Conductivity (S/cm)
HLW-ALG-11	950	0.180	1050	0.307
	1047	0.317	1100	0.370
	1143	0.394	1150	0.430
	1239	0.547	1200	0.487
HLW-ALG-12	937	0.227	1050	0.389
	1034	0.359	1100	0.460
	1130	0.518	1150	0.529
	1224	0.617	1200	0.596
HLW-ALG-13	944	0.134	1050	0.238
	1042	0.229	1100	0.298
	1138	0.350	1150	0.364
	1231	0.484	1200	0.438
HLW-ALG-14	941	0.151	1050	0.278
	1031	0.252	1100	0.350
	1120	0.382	1150	0.429
	1209	0.531	1200	0.515
HLW-ALG-15	943	0.226	1050	0.378
	1034	0.351	1100	0.455
	1123	0.495	1150	0.534
	1213	0.632	1200	0.613
HLW-ALG-16	947	0.249	1050	0.391
	1038	0.377	1100	0.477
	1129	0.494	1150	0.574
	1221	0.765	1200	0.682
HLW-ALG-17	940	0.202	1050	0.325
	1031	0.307	1100	0.391
	1122	0.414	1150	0.464
	1214	0.571	1200	0.543
HLW-ALG-18	943	0.189	1050	0.309
	1034	0.291	1100	0.372
	1125	0.403	1150	0.440
	1217	0.538	1200	0.512
HLW-ALG-19	952	0.217	1050	0.338
	1040	0.329	1100	0.408
	1127	0.446	1150	0.482
	1215	0.582	1200	0.560
HLW-ALG-20	959	0.291	1050	0.441
	1048	0.437	1100	0.532
	1136	0.602	1150	0.630
	1226	0.787	1200	0.732

Table 4.5. Measured and Fitted Electrical Conductivity Data for HLW Algorithm Glasses (continued).

Glass ID	Measured Electrical Conductivity		Fitted Electrical Conductivity	
	Temperature (°C)	Conductivity (S/cm)	Temperature (°C)	Conductivity (S/cm)
HLW-ALG-21	933	0.233	1050	0.405
	1030	0.366	1100	0.477
	1125	0.548	1150	0.546
	1217	0.610	1200	0.613
HLW-ALG-22	941	0.251	1050	0.449
	1030	0.404	1100	0.546
	1127	0.612	1150	0.644
	1223	0.780	1200	0.742
HLW-ALG-23	942	0.380	1050	0.624
	1042	0.579	1100	0.731
	1139	0.879	1150	0.833
	1235	0.951	1200	0.928
HLW-ALG-24	941	0.145	1050	0.280
	1039	0.313	1100	0.336
	1134	0.360	1150	0.391
	1232	0.452	1200	0.442
HLW-ALG-25	941	0.213	1050	0.380
	1039	0.388	1100	0.452
	1135	0.482	1150	0.520
	1231	0.623	1200	0.585
HLW-ALG-26	952	0.122	1050	0.199
	1051	0.202	1100	0.250
	1148	0.300	1150	0.308
	1244	0.443	1200	0.374
HLW-ALG -27[a]	973	0.288	1050	0.408
	1066	0.442	1100	0.491
	1155	0.576	1150	0.577
	1247	0.752	1200	0.664
HLW-ALG-28	952	0.243	1050	0.376
	1041	0.365	1100	0.448
	1129	0.490	1150	0.523
	1214	0.621	1200	0.599
HLW-ALG-29	963	0.222	1050	0.356
	1055	0.364	1100	0.441
	1136	0.504	1150	0.529
	1237	0.688	1200	0.620
HLW-ALG-30	924	0.226	1050	0.386
	1032	0.353	1100	0.458
	1128	0.514	1150	0.532
	1222	0.636	1200	0.609

[a] Apparent phase separation observed.

Table 4.5. Measured and Fitted Electrical Conductivity Data for HLW Algorithm Glasses (continued).

Glass ID	Measured Electrical Conductivity		Fitted Electrical Conductivity	
	Temperature (°C)	Conductivity (S/cm)	Temperature (°C)	Conductivity (S/cm)
HLW-ALG-31	975	0.144	1050	0.202
	1073	0.220	1100	0.253
	1173	0.329	1150	0.311
	1270	0.498	1200	0.376
HLW-ALG-32	950	0.152	1050	0.261
	1048	0.254	1100	0.330
	1145	0.408	1150	0.408
	1243	0.572	1200	0.495
HLW-ALG-33	958	0.317	1050	0.463
	1056	0.478	1100	0.549
	1154	0.637	1150	0.638
	1251	0.828	1200	0.729
HLW-ALG-34	930	0.265	1050	0.435
	1028	0.404	1100	0.520
	1127	0.555	1150	0.616
	1225	0.787	1200	0.720
HLW-ALG-35	951	0.115	1050	0.209
	1048	0.206	1100	0.266
	1144	0.323	1150	0.328
	1239	0.446	1200	0.393
HLW-ALG-36	956	0.177	1050	0.310
	1055	0.320	1100	0.392
	1151	0.480	1150	0.480
	1248	0.667	1200	0.573
HLW-ALG-37	929	0.096	1050	0.204
	1026	0.177	1100	0.255
	1120	0.279	1150	0.308
	1212	0.374	1200	0.362
HLW-ALG-38	955	0.101	1050	0.164
	1052	0.155	1100	0.204
	1148	0.268	1150	0.249
	1243	0.332	1200	0.298
HLW-ALG-39	940	0.128	1050	0.226
	1038	0.213	1100	0.278
	1135	0.318	1150	0.333
	1230	0.427	1200	0.392
HLW-ALG-40	949	0.221	1050	0.374
	1046	0.370	1100	0.450
	1141	0.527	1150	0.525
	1231	0.626	1200	0.598

Table 4.6. Temperature and Volume %-Crystallinity Data for HLW Algorithm Glasses.

Glass ID	Heat-Treatment Temperature (°C)												
	650	700	750	775	800	850	900	950	1000	1050	1100	1150	1200
HLW-ALG-01	< 0.1	<0.1	0.1	—[a]	0.1	0.2	—	< 0.1	—	0.0	—	—	—
HLW-ALG-02	—	0.1	0.2	—	0.3	0.3	—	< 0.1	—	< 0.1	—	—	—
HLW-ALG-03	—	—	0.2	—	**0.7**[b]	**0.5**	**0.1**	0.0	—	0.0	—	—	—
HLW-ALG-04	—	0.5	0.1	—	0.2	0.1	—	0.0	—	—	—	—	—
HLW-ALG-05	—	**2.3**	**2.7**	—	**1.9**	**2.5**	—	**1.2**	**0.5**	**0.3**	—	—	—
HLW-ALG-06	—	25.6	24.6	—	21.0	**2.6**	**1.5**	**0.7**	**1.0**	—	—	—	—
HLW-ALG-07	—	< 0.1	< 0.1	—	0.1	<0.1	< 0.1	< 0.1	—	—	—	—	—
HLW-ALG-08	—	—	—	—	—	—	13.6	9.2	4.8	**1.9**	**1.6**	**1.1**	**0.8**
HLW-ALG-09	—	**1.1**	**1.0**	—	**1.1**	—	**1.0**	**0.5**	**0.3**	—	—	—	—
HLW-ALG-10	—	3.5	0.5	0.7	**0.8**	**0.6**	**0.2**	—	—	—	—	—	—
HLW-ALG-11	0.7	—	1.2	—	1.7	**3.9**	**4.6**	**3.8**	**2.1**	**2.7**	**2.6**	—	**1.1**
HLW-ALG-12	—	—	0.4	—	**1.5**	**0.6**	**1.3**	**0.4**	**0.3**	< 0.1	—	—	—
HLW-ALG-13	—	—	—	—	11.3	9.5	**5.6**	**3.9**	—	**3.0**	**2.9**	**3.4**	**2.9**
HLW-ALG-14	—	—	—	—	**3.3**	**2.6**	**2.8**	**1.9**	**0.7**	< 0.1	—	—	—
HLW-ALG-15	—	0.2	0.5	—	**1.0**	**0.7**	**0.5**	0.8	—	—	—	—	—
HLW-ALG-16	< 0.1	0.1	< 0.1	—	0.1	0.1	—	—	—	—	—	—	—
HLW-ALG-17	—	1.5	0.3	**4.7**	**0.7**	**0.3**	0.5	—	—	—	—	—	—
HLW-ALG-18	**0.8**	**0.1**	< 0.1	—	0.1	0.0	—	—	—	—	—	—	—
HLW-ALG-19	—	0.3	0.1	—	0.4	**0.7**	**0.5**	**0.4**	—	—	—	—	—
HLW-ALG-20	—	0.4	**0.6**	—	**0.5**	**0.6**	**0.3**	**0.2**	—	—	—	—	—
HLW-ALG-21	—	0.4	0.8	—	3.4	7.5	10.4	7.8	3.0	**1.2**	**1.3**	**1.6**	**0.2**
HLW-ALG-22	—	< 0.1	< 0.1	—	0.1	0.8	3.1	**5.5**	**0.6**	—	—	—	—
HLW-ALG-23	0.1	—	—	—	1.9	3.4	**9.3**	**5.9**	**2.6**	—	—	—	—
HLW-ALG-24	—	—	—	—	—	**11.5**	**6.7**	0.7	—	**5.2**	**5.7**	**4.3**	**4.5**
HLW-ALG-25	—	2.9	**1.0**	—	**1.0**	**0.6**	**0.5**	—	—	—	—	—	—
HLW-ALG-26	0.1	0.1	< 0.1	—	0.1	< 0.1	—	0.1	—	—	—	—	—
HLW-ALG-27	—	**16.9**	**14.0**	—	**0.4**	< 0.1	< 0.1	—	—	—	—	—	—
HLW-ALG-28	—	0.5	0.4	—	**2.0**	**1.0**	**0.3**	—	—	—	—	—	—
HLW-ALG-29	0.1	0.1	0.4	—	0.8	0.9	—	—	—	—	—	—	—
HLW-ALG-30	—	**1.1**	—	—	**0.7**	**0.6**	—	**0.1**	—	—	—	—	—
HLW-ALG-31	—	—	—	—	—	**2.2**	—	**1.7**	**1.0**	**0.5**	**0.2**	—	—
HLW-ALG-32	—	—	—	—	—	**6.3**	—	**3.4**	**2.8**	**1.9**	**2.4**	**0.4**	**0.1**
HLW-ALG-33	—	—	29.8	—	—	5.1	—	**1.9**	**2.2**	**1.4**	**1.5**	**1.0**	**0.5**
HLW-ALG-34	—	—	—	—	**1.1**	**0.9**	**0.5**	**0.1**	< 0.1	—	—	—	—
HLW-ALG-35	—	—	—	—	—	**3.8**	**1.8**	**1.1**	**1.5**	**1.1**	< 0.1	—	—
HLW-ALG-36	—	—	—	—	—	**3.3**	**1.7**	**1.7**	**2.6**	**1.0**	**0.4**	—	—
HLW-ALG-37	—	—	—	—	—	—	3.5	2.9	**4.1**	**3.6**	**3.2**	—	**3.1**
HLW-ALG-38	—	—	—	—	**3.8**	**3.9**	**2.8**	**2.8**	**2.4**	**1.9**	**1.3**	—	—
HLW-ALG-39	—	—	—	—	< 0.1	0.2	< 0.1	0.2	< 0.1	—	—	—	—
HLW-ALG-40	—	—	—	—	—	**2.1**	**1.8**	**1.5**	**1.0**	**0.9**	**0.3**	—	—

[a] — indicates empty data field; no data were collected for these heat-treatment temperatures.
[b] Only data in boldface were included in the regression to estimate $T_{1\%}$ values.

Table 4.7. Regression Results[a], Estimated $T_{1\%}$, and the Major Crystalline Phase Near $T_{1\%}$ for HLW Algorithm Glasses.

Glass ID	Intercept	Slope	$T_{1\%}$ (°C)	Crystalline Phase
HLW-ALG-01	ND[b]	ND	ND	Spinel + RuO_2
HLW-ALG-02	ND	ND	ND	Spinel + RuO_2
HLW-ALG-03	919.64	-160.71	758.9	Spinel
HLW-ALG-04	ND	ND	ND	Spinel
HLW-ALG-05	1072.84	-123.67	949.2	Spinel
HLW-ALG-06	1022.13	-66.99	955.1	Spinel
HLW-ALG-07	ND	ND	ND	RuO_2
HLW-ALG-08	1300.68	-130.14	1170.5	ZrO_2
HLW-ALG-09	1095.79	-294.94	800.8	Spinel
HLW-ALG-10	935.71	-160.71	775.0	Spinel
HLW-ALG-11	1270.42	-88.60	1181.8	ZrO_2 + ThO_2
HLW-ALG-12	989.73	-109.43	880.3	Spinel
HLW-ALG-13[c]	1382.96	-89.76	1293.2	ZrO_2 + ThO_2
HLW-ALG-14	1064.54	-72.80	991.7	Spinel
HLW-ALG-15	994.74	-197.37	797.4	Spinel
HLW-ALG-16	ND	ND	ND	Spinel + RuO_2
HLW-ALG-17	832.40	-12.67	819.7	Spinel + Na(Mn,Fe,Ni) Silicate
HLW-ALG-18[d]	707.14	-71.43	635.7	Spinel
HLW-ALG-19[c]	1071.43	-321.43	750.0	Spinel
HLW-ALG-20[c]	1016.67	-378.79	637.9	Spinel
HLW-ALG-21	1193.22	-63.85	1129.4	ZrO_2 + ThO_2
HLW-ALG-22[d]	1006.12	-10.20	995.9	ZrO_2 + ThO_2
HLW-ALG-23	1038.55	-14.92	1023.6	$Na_2ZrSi_2O_7$ + ZrO_2
HLW-ALG-24[c]	1322.20	-44.41	1277.8	ZrO_2 + ThO_2
HLW-ALG-25	1002.41	-228.92	773.5	Spinel
HLW-ALG-26	ND	ND	ND	ThO_2 + RuO_2
HLW-ALG-27	805.46	-5.32	800.1	Spinel + NaAlFe silicate
HLW-ALG-28	914.04	-58.22	855.8	Spinel
HLW-ALG-29	ND	ND	ND	Spinel
HLW-ALG-30	982.02	-251.23	730.8	Spinel
HLW-ALG-31	1117.98	-114.26	1003.7	Spinel
HLW-ALG-32	1180.54	-55.71	1124.8	Spinel
HLW-ALG-33	1274.04	-140.50	1133.5	ZrO_2 + Spinel
HLW-ALG-34	968.64	-144.07	824.6	Spinel
HLW-ALG-35	1054.93	-56.41	998.5	Spinel
HLW-ALG-36	1100.30	-70.59	1029.7	Spinel
HLW-ALG-37[c]	1680.24	-169.35	1510.9	ZrO_2 + ThO_2
HLW-ALG-38	1249.72	-111.01	1138.7	ZrO_2 + ThO_2 + Spinel
HLW-ALG-39	ND	ND	ND	Spinel
HLW-ALG-40	1152.76	-140.34	1012.4	Spinel

[a] Regression results are rounded to 2 decimal places for the intercept and slope, 1 decimal place for $T_{1\%}$ values.
[b] ND = Not determined (Regression was not performed).
[c] $T_{1\%}$ estimated by large extrapolation (i.e., > 100°C).
[d] Regression performed with 2 data points.

Table 4.8. PCT Release Data (Leachate Concentration in ppm and Normalized Release in g/l) for the CCC Samples of Selected HLW Algorithm Glasses[(a)].

Sample ID	PCT-B (ppm)	PCT-Li (ppm)	PCT-Na (ppm)	PCT-B (g/l)	PCT-Li (g/l)	PCT-Na (g/l)	Leachate pH
HLW-ALG-01CCC	29.7	10.8	102.1	0.90	0.70	0.80	10.94
HLW-ALG-03CCC	347.1	112.7	1089.0	12.97	7.94	7.74	12.11
HLW-ALG-08CCC	3.6	6.1	69.7	0.24	0.63	0.67	11.20
HLW-ALG-11CCC	11.8	11.7	15.15	0.31	0.42	0.34	10.32
HLW-ALG-14CCC	7.0	24.6	22.4	0.47	0.88	0.63	11.04
HLW-ALG-27CCC	1641.0	274.4	1720.0	37.68	30.65	13.18	9.98
HLW-ALG-29CCC	46.7	7.0	101.7	1.07	0.79	0.78	10.52
HLW-ALG-32CCC	4.3	10.2	33.6	0.29	0.55	0.49	11.02
HLW-ALG-33CCC	188.8	93.7	439.4	7.59	5.33	3.35	11.94
HLW-ALG-34CCC	430.6	64.9	1543.0	16.87	6.91	10.95	11.99

[(a)] Leachate concentration rounded to 1 decimal place; normalized release and leachate pH rounded to 2 decimal places.

Table 4.9. Vol%-Crystallinity Data for the CCC Samples of Selected HLW Algorithm Glasses.

Sample ID	Crystallinity
HLW-ALG-01CCC	< 0.1 vol% of Cr-rich spinel and 0.2 vol% of Na(Al, Fe) silicate
HLW-ALG-03CCC	< 0.1 vol% of spinel
HLW-ALG-08CCC	1.9 vol% crystals (70% spinel + 30% zirconia with trace amount of thoria)
HLW-ALG-11CCC	4.7 vol% crystals (80% zirconia + 20% thoria)
HLW-ALG-14CCC	1.2 vol% of spinel
HLW-ALG-27CCC	1.4 vol% of spinel + 20 vol% of $NaAlSiO_4$
HLW-ALG-29CCC	0.2 vol% of spinel
HLW-ALG-32CCC	2.5 vol% of spinel
HLW-ALG-33CCC	2.9 vol% of spinel and zirconia + 15 vol% of $NaAlSiO_4$
HLW-ALG-34CCC	0.1 vol% of spinel

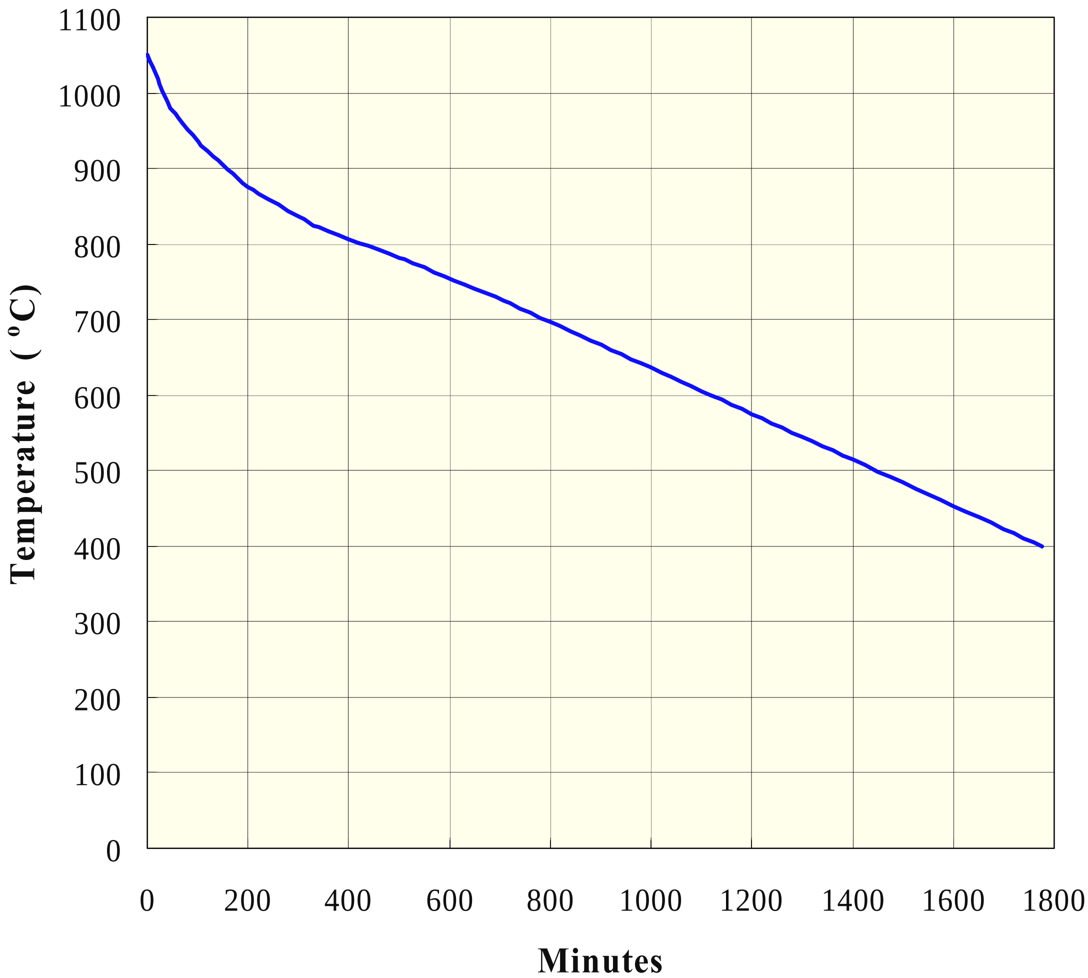


Figure 3.1. HLW canister centerline cooling (CCC) temperature profile.

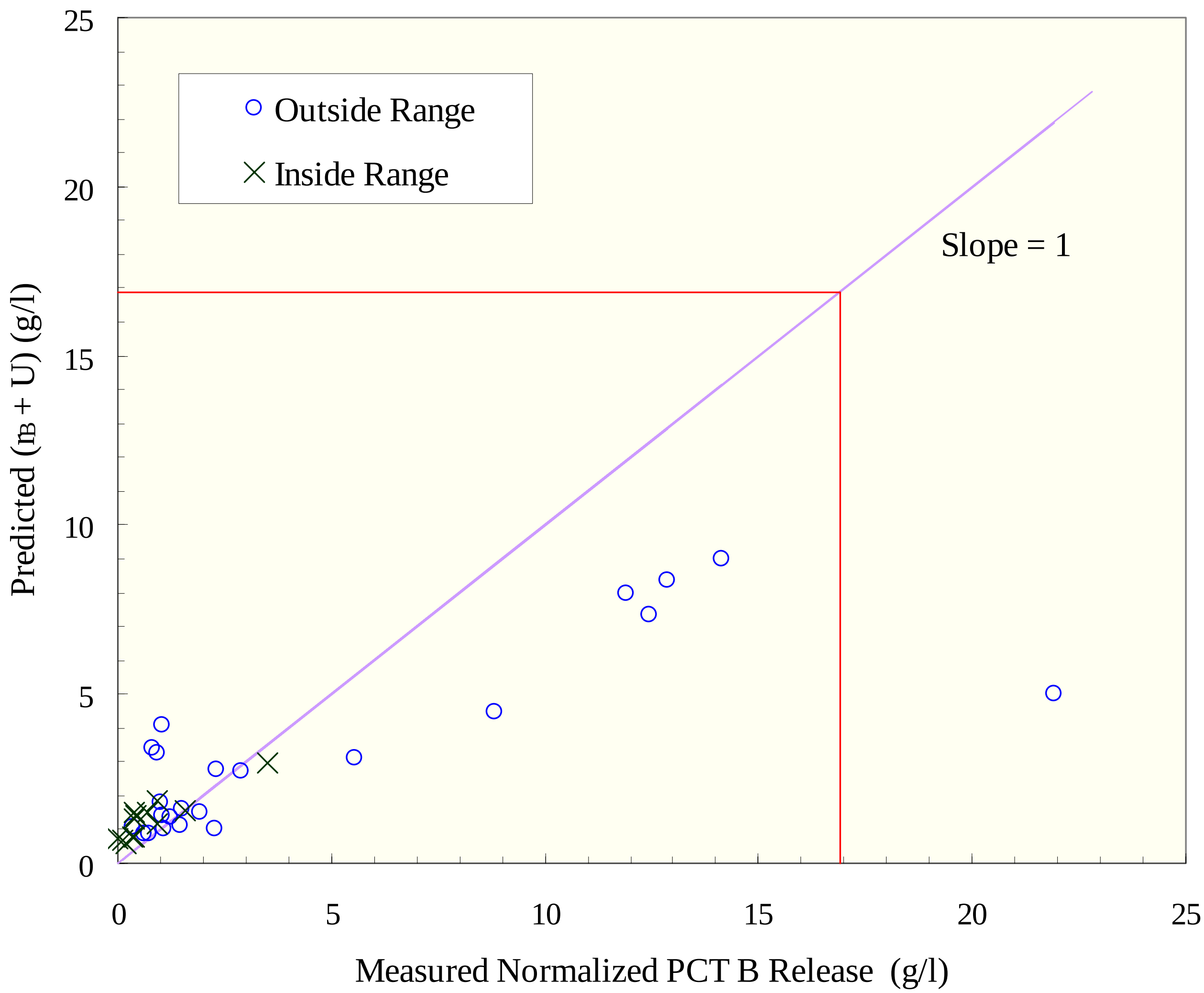


Figure 4.1. Comparison of Predicted Normalized PCT Boron Releases (Plus Uncertainty U) with Measured Values. (Glasses are identified according to whether they are inside or outside the compositional ranges of glasses used to develop the Phase 1 PCT models. The constraint limit at 16.7 g/l is also shown.)

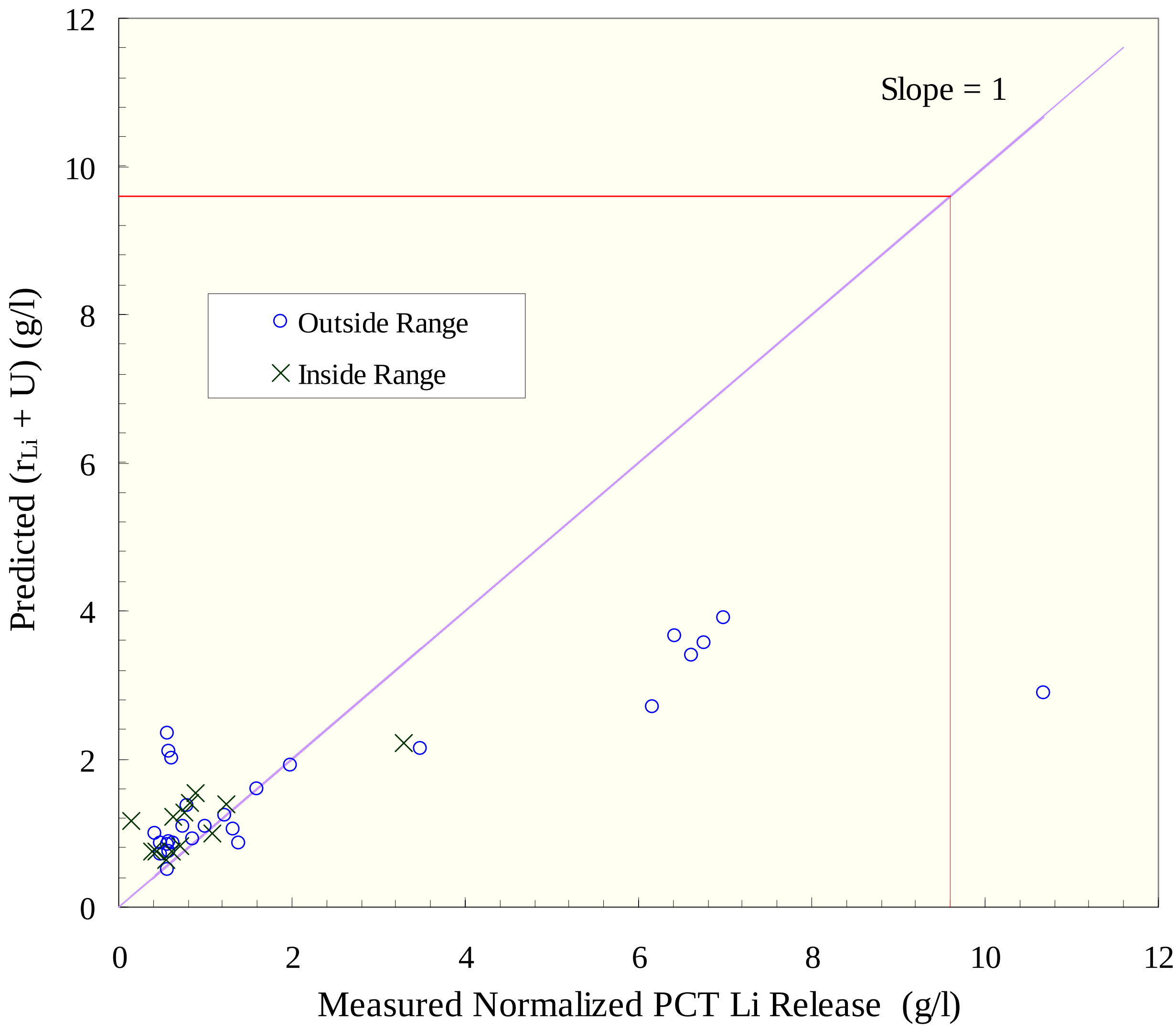


Figure 4.2. Comparison of Predicted Normalized PCT Lithium Releases (Plus Uncertainty U) with Measured Values. (Glasses are identified according to whether they are inside or outside the compositional ranges of glasses used to develop the Phase 1 PCT models. The constraint limit at 9.6 g/l is also shown.)

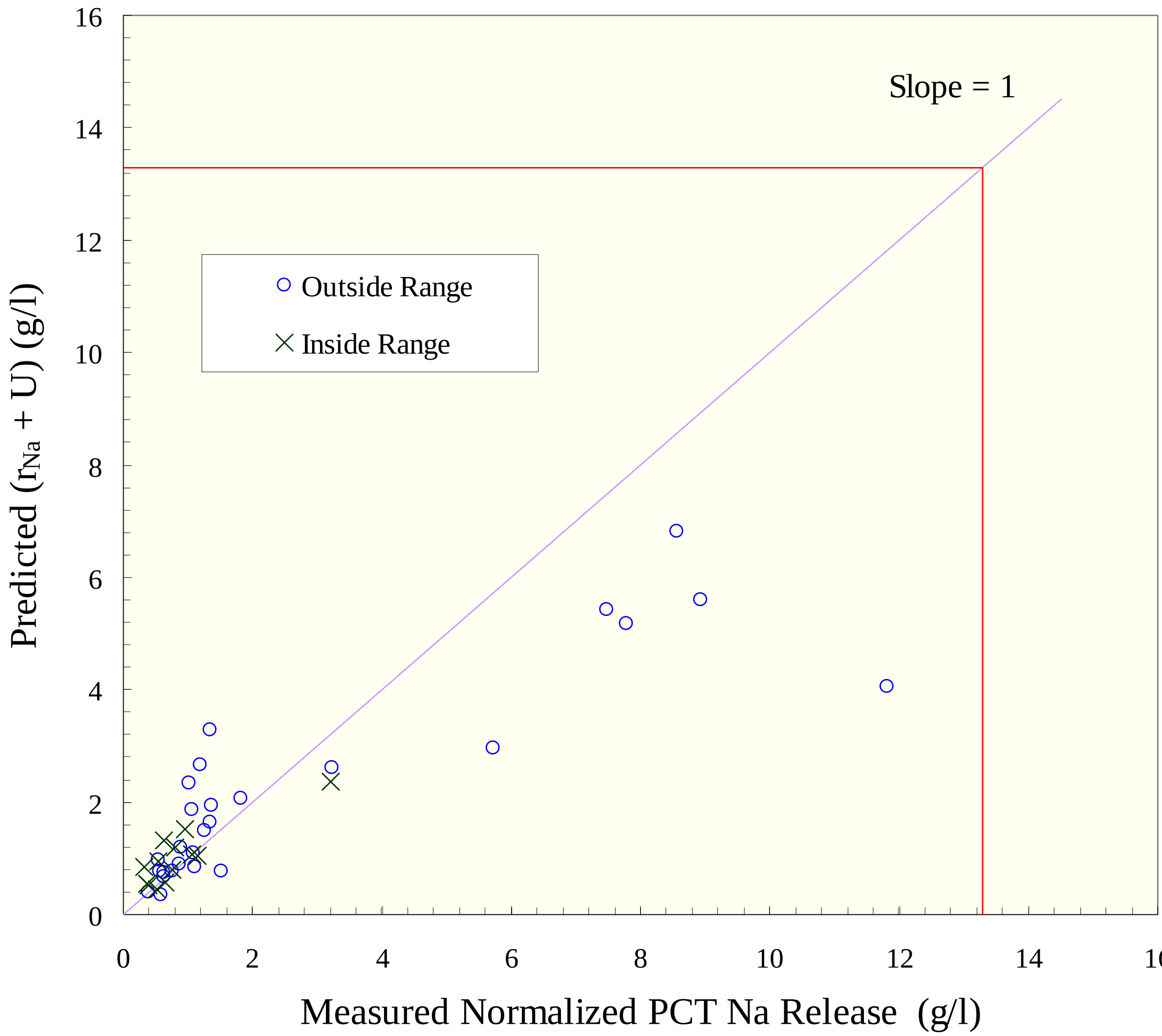


Figure 4.3. Comparison of Predicted Normalized PCT Sodium Releases (Plus Uncertainty U) with Measured Values. (Glasses are identified according to whether they are inside or outside the compositional ranges of glasses used to develop the Phase 1 PCT models. The constraint limit at 13.3 g/l is also shown.)

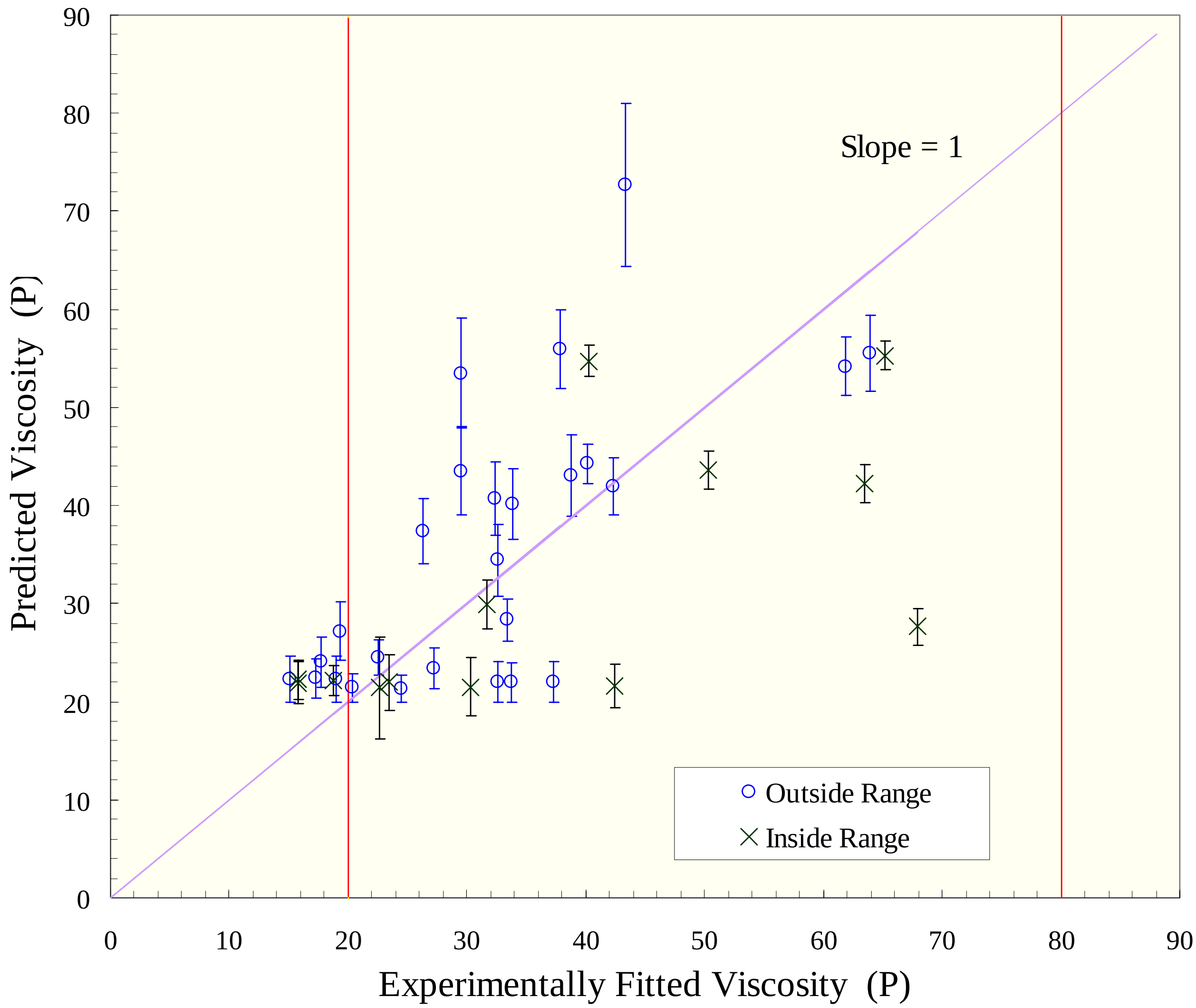


Figure 4.4. Comparison of Predicted and Experimentally Fitted Viscosity at 1150ºC for the HLW Algorithm Glasses. (Glasses are identified according to whether they are inside or outside the compositional ranges of glasses used to develop the Phase 1 viscosity models. The constraint limits are indicated by the vertical lines.)

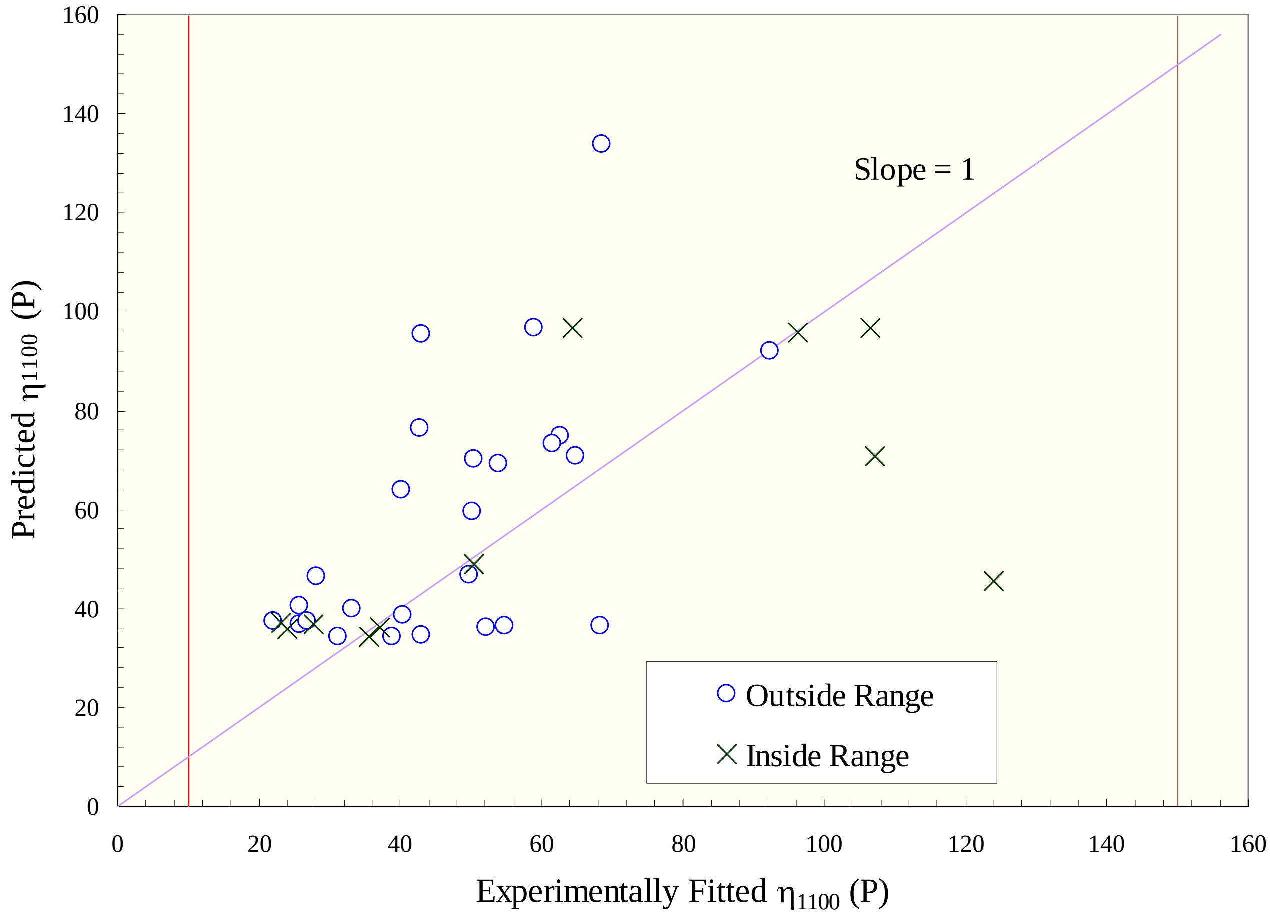


Figure 4.5. Comparison of Predicted and Experimentally Fitted Viscosity at 1100ºC (η_{1100}) for the HLW Algorithm Glasses. (Glasses are identified according to whether they are inside or outside the compositional ranges of glasses used to develop the Phase 1 viscosity models. The constraint limits are indicated by the vertical lines.)

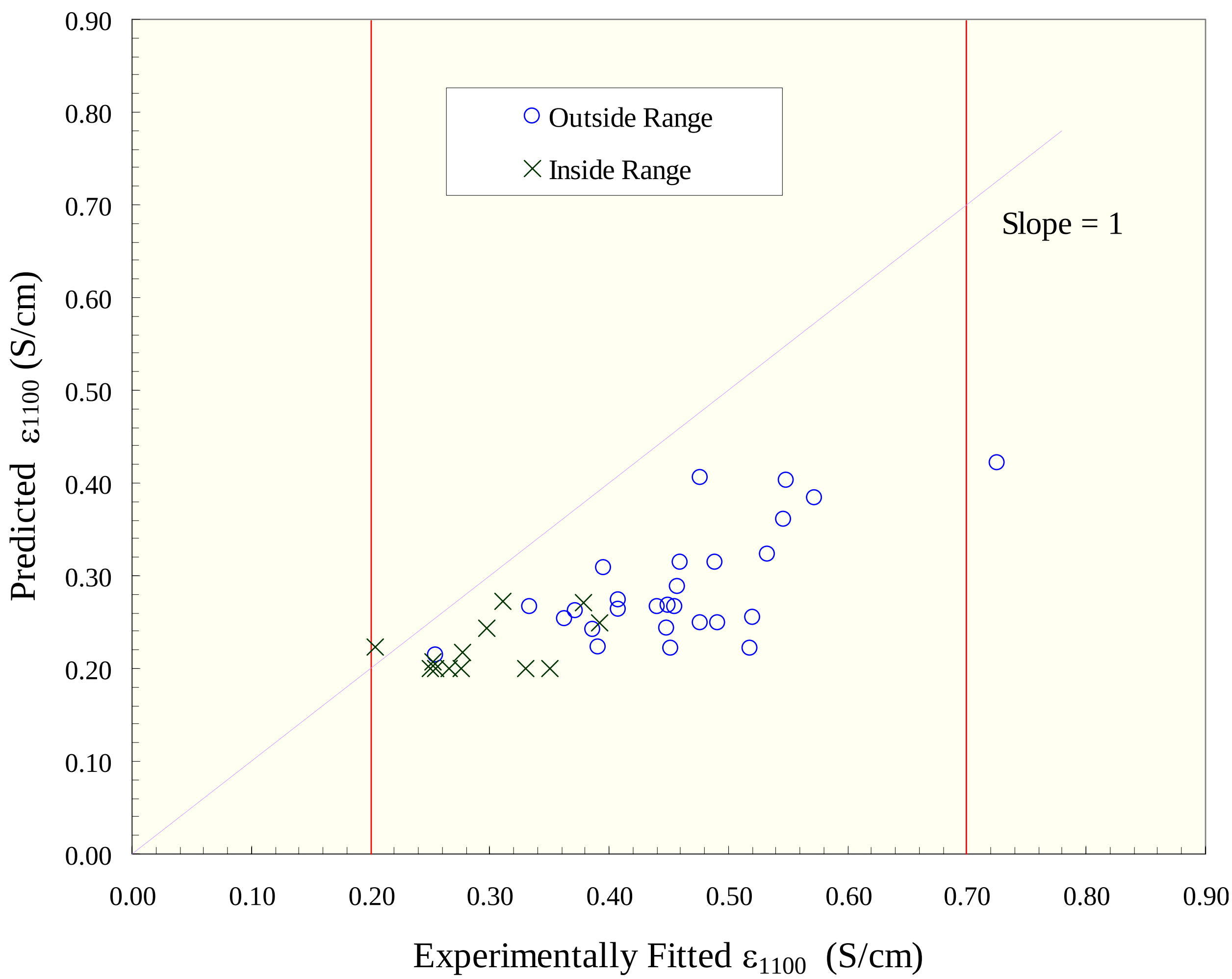


Figure 4.6. Comparison of Predicted and Experimentally Fitted Electrical Conductivity at 1100°C (ε_{1100}) for the HLW Algorithm Glasses. (Glasses are identified according to whether they are inside or outside the compositional ranges of glasses used to develop the Phase 1 electrical conductivity models. The constraint limits are indicated by the vertical lines.)

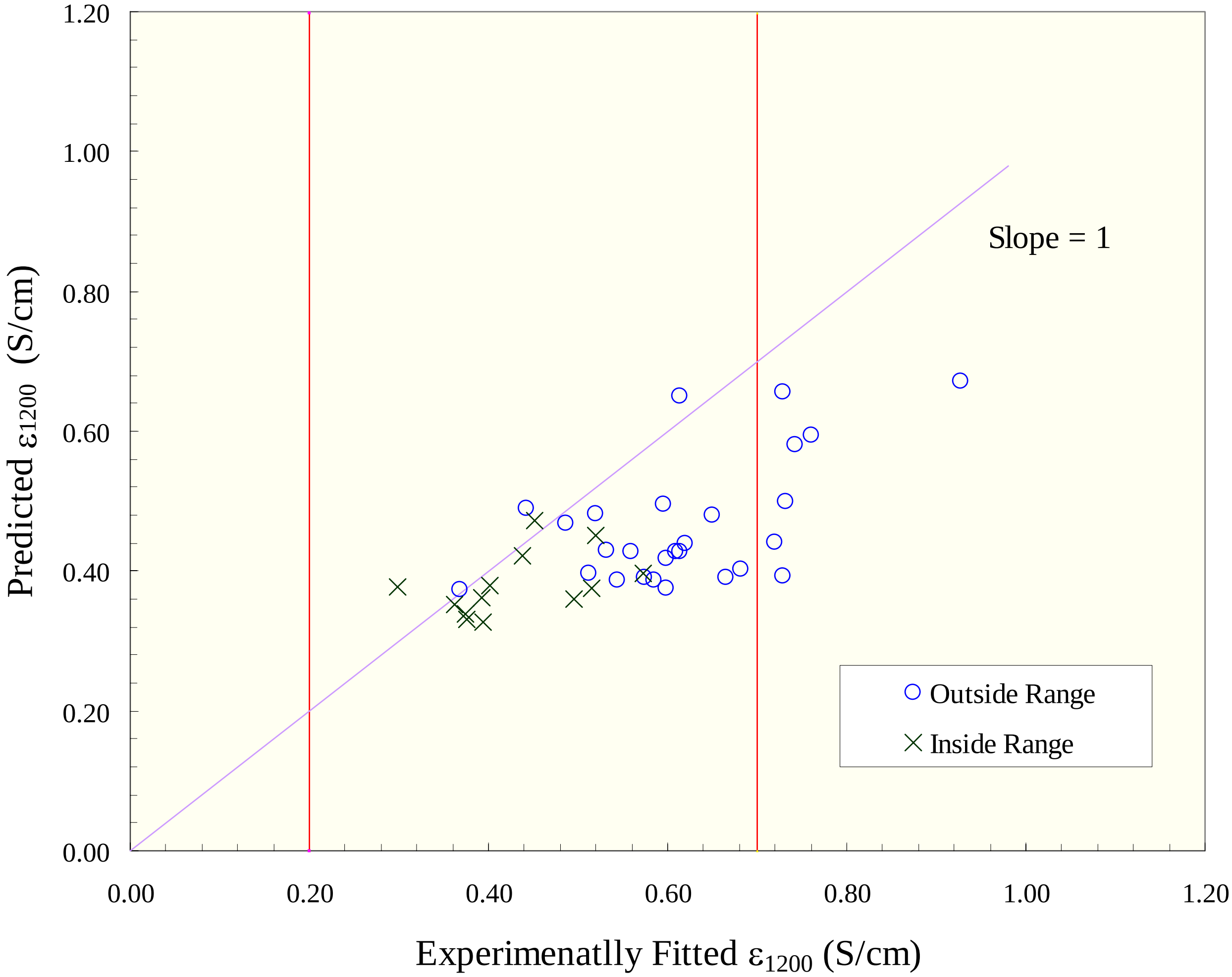


Figure 4.7. Comparison of Predicted and Experimentally Fitted Electrical Conductivity at 1200°C (ε_{1200}) for the HLW Algorithm Glasses. (Glasses are identified according to whether they are inside or outside the compositional ranges of glasses used to develop the Phase 1 electrical conductivity models. The constraint limits are indicated by the vertical lines.)

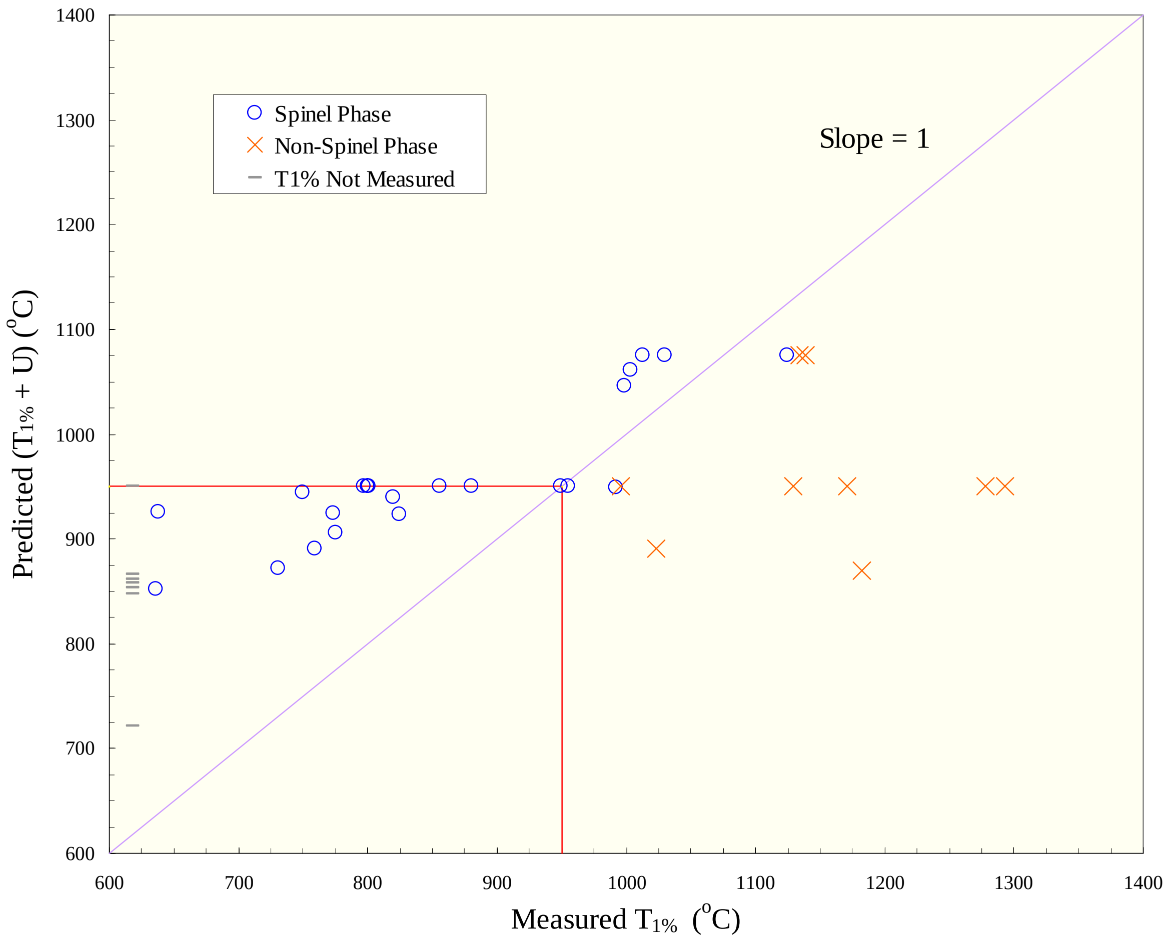


Figure 4.8. Comparison of Predicted and Measured $T_{1\%}$ Values for the HLW Algorithm Glasses. (The symbols identify the primary crystalline phases. The predicted values for glasses with undetermined $T_{1\%}$ are included for comparison and are identified by the symbol −. One outlier is excluded from the plot.)

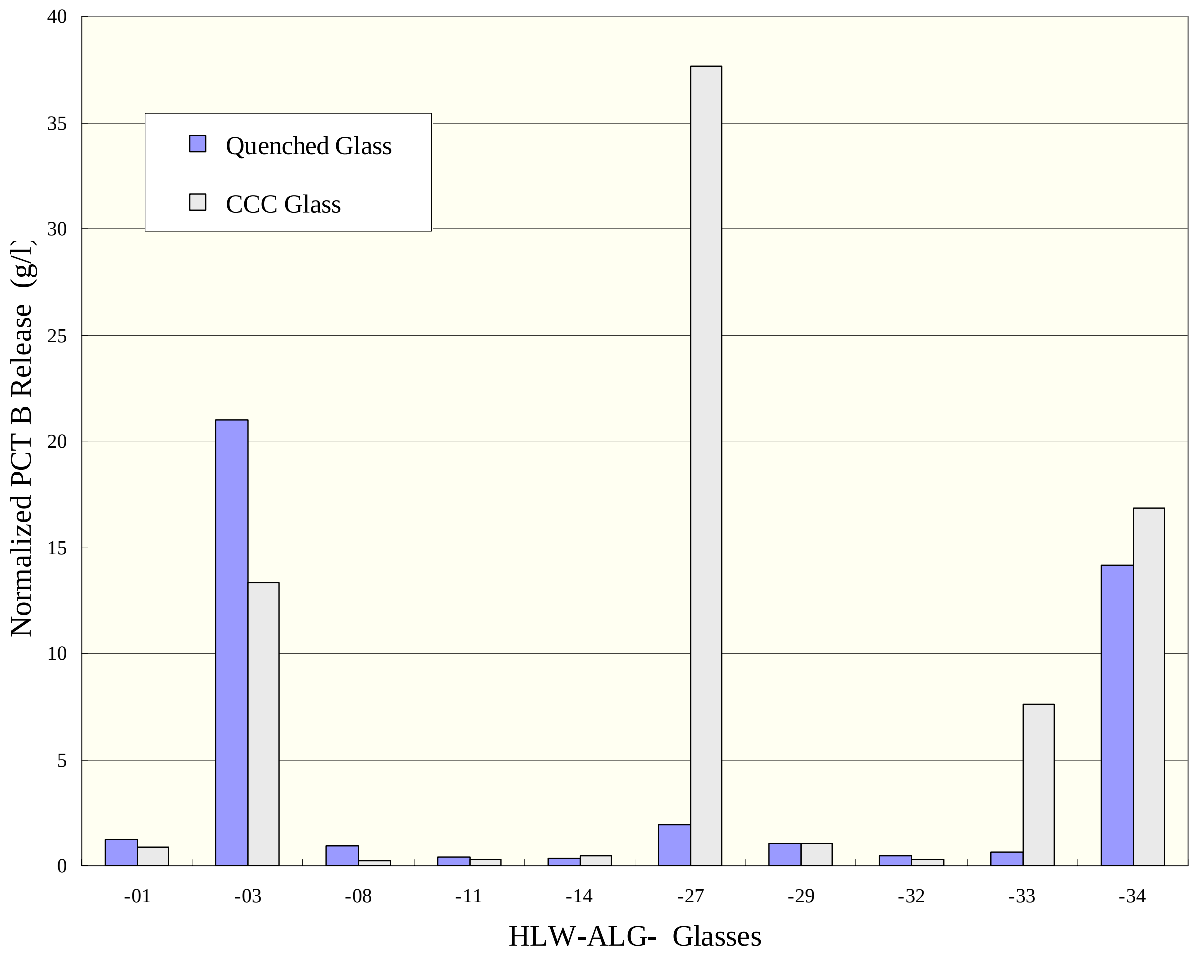


Figure 4.9. Comparison of PCT Normalized Boron Releases for CCC Samples with Their As-Melted (Quenched) Counterparts.

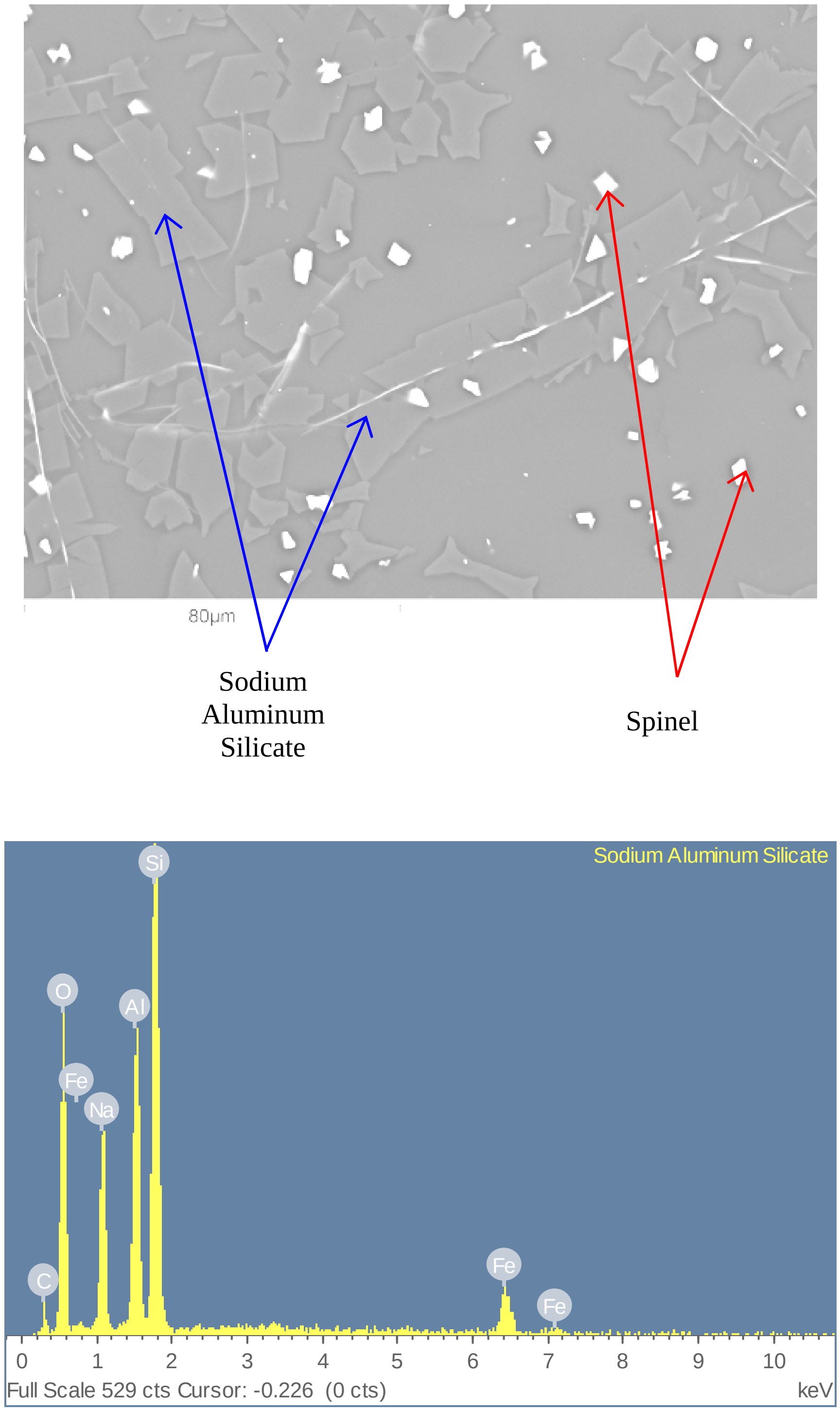
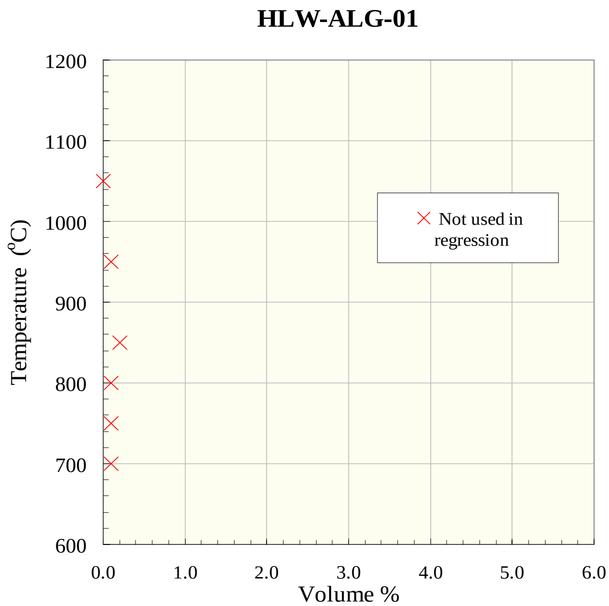
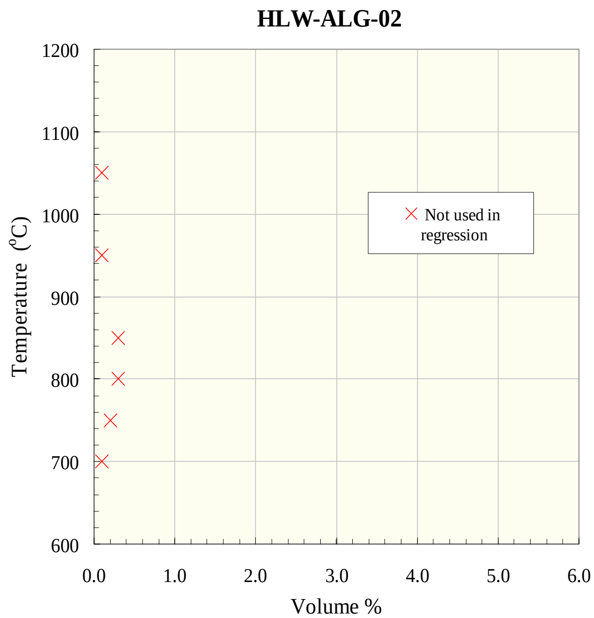


Figure 4.10. Scanning Electron Micrograph of a Canister Centerline Cooled Sample of HLW-ALG-27 (Top) and X-Ray Energy Dispersive Spectrum Identifying the Secondary Phase (Bottom).

Appendix A
Plots of Heat Treatment and Regression Data

This appendix presents graphically heat treatment data collected for the WTP HLW Algorithm glasses. For each of the 40 algorithm glasses, the volume % crystallinity data measured after heat treatment are plotted against the heat treatment temperatures (heat treatment time = 70 hours, after 1 hour at 1200°C). Regression of the data results in linear correlations from which $T_{1\%}$ values can be estimated; the regression results are included in the plots (except for 8 glasses for which no regression was performed). To the extent possible, similar scales are used in the plots to facilitate comparison.


HLW-ALG-01
Temperature (°C)
Volume %
Not used in regression
1200
1100
1000
900
800
700
600
0.0
1.0
2.0
3.0
4.0
5.0
6.0


HLW-ALG-02
Temperature (°C)
Volume %
Not used in regression
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1100
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900
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2.0
3.0
4.0
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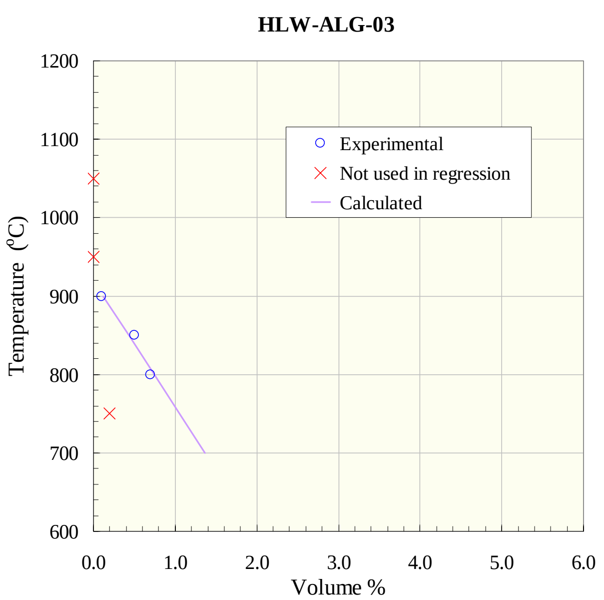
6.0


HLW-ALG-03
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
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1000
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700
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3.0
4.0
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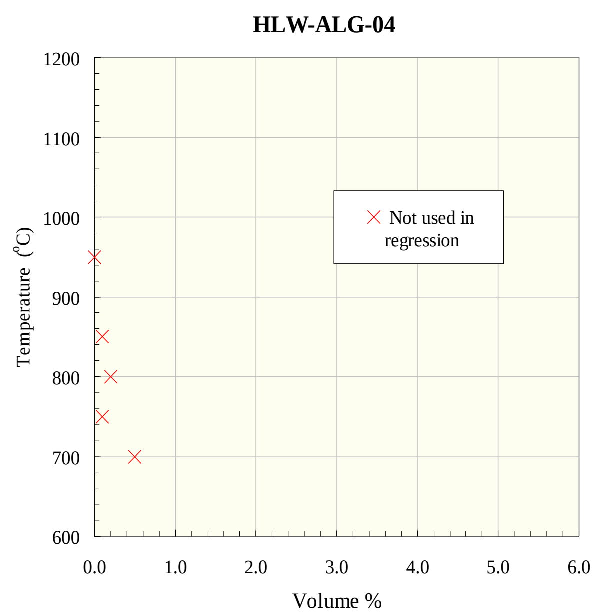
HLW-ALG-04
Temperature (°C)
Volume %
Not used in regression
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900
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2.0
3.0
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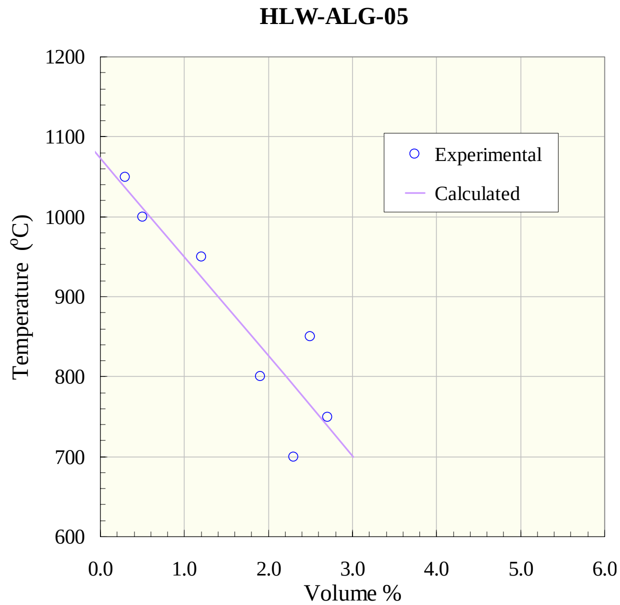
6.0


HLW-ALG-05
Experimental
Calculated
Temperature (°C)
Volume %
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900
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2.0
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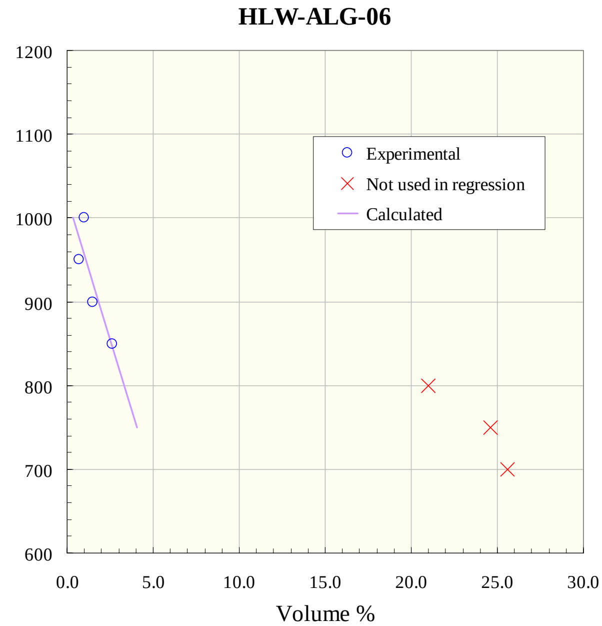
6.0


HLW-ALG-06
Experimental
Not used in regression
Calculated
Volume %
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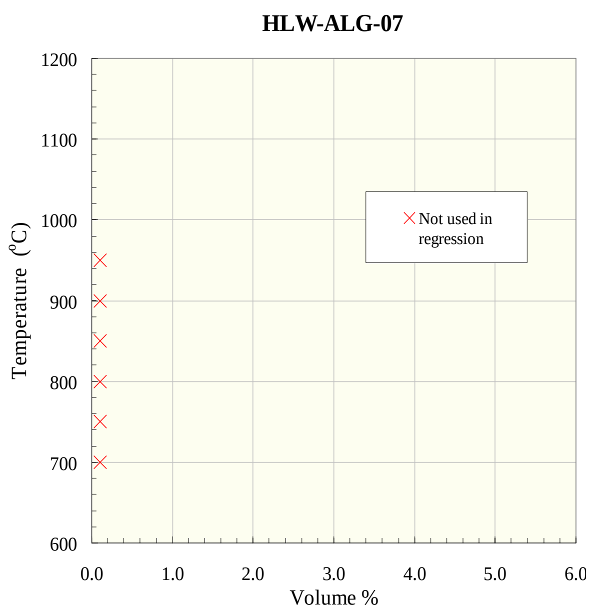
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Not used in regression
Temperature (°C)
Volume %
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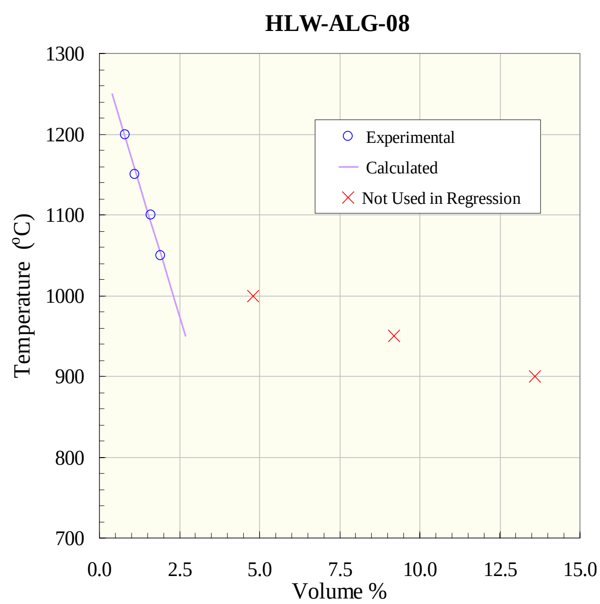
HLW-ALG-08
Experimental
Calculated
Not Used in Regression
Temperature (°C)
Volume %
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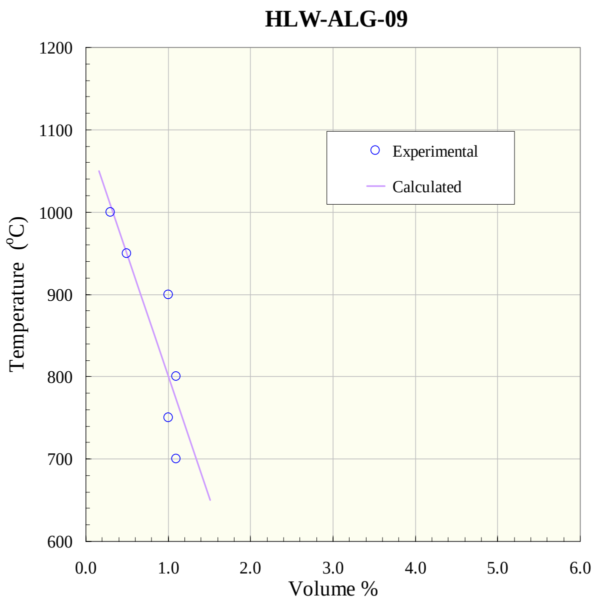
7.5
10.0
12.5
15.0


HLW-ALG-09
Experimental
Calculated
Temperature (°C)
Volume %
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900
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700
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2.0
3.0
4.0
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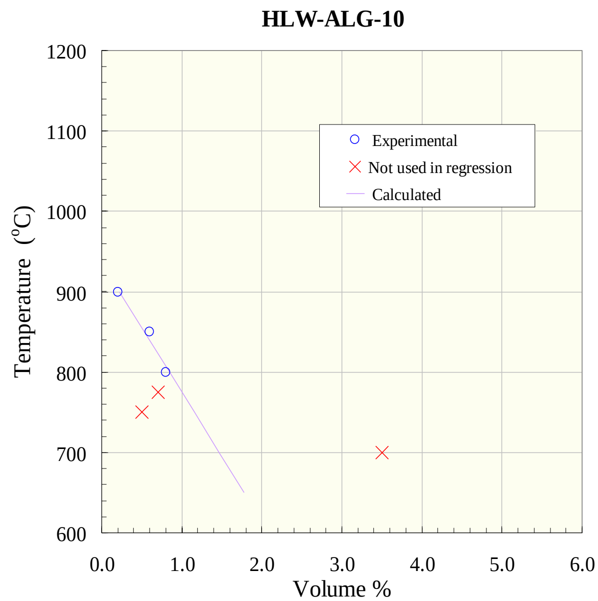
6.0


HLW-ALG-10
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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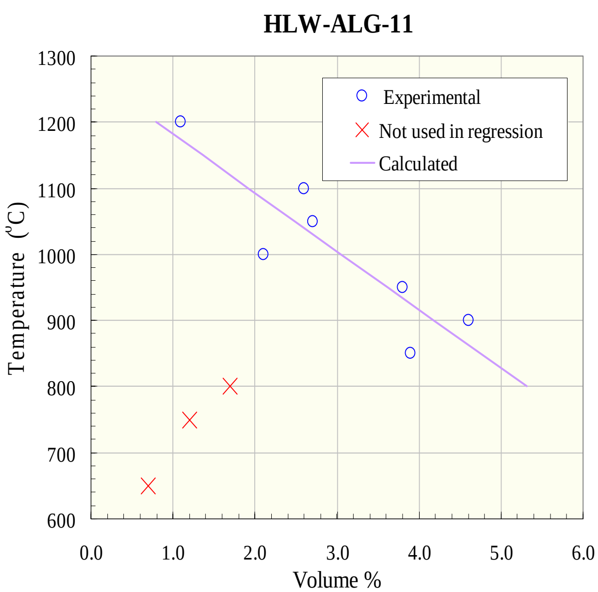
6.0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Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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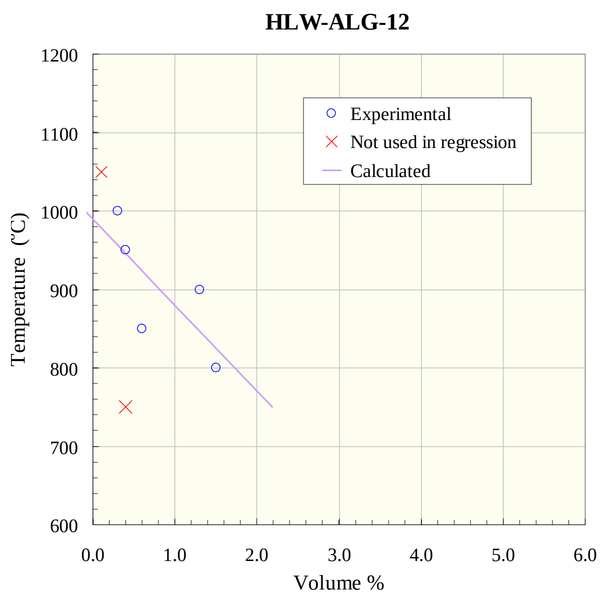
2.0
3.0
4.0
5.0
6.0


HLW-ALG-12
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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900
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2.0
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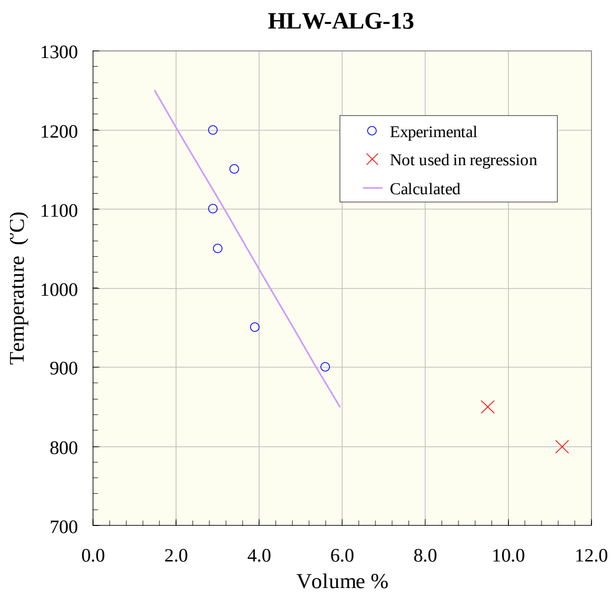
5.0
6.0


HLW-ALG-13
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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4.0
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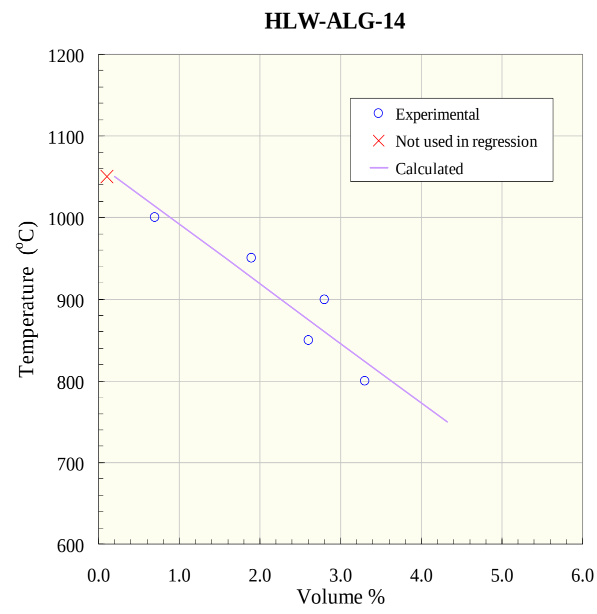
8.0
10.0
12.0


HLW-ALG-14
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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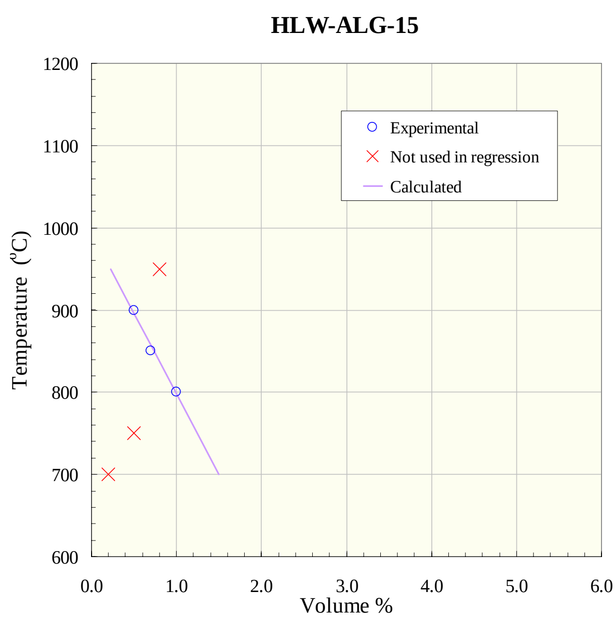
HLW-ALG-15
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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900
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700
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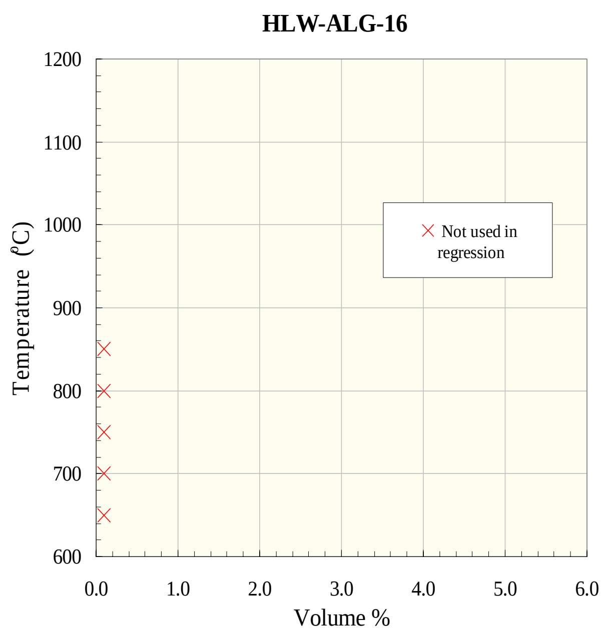
1.0
2.0
3.0
4.0
5.0
6.0


HLW-ALG-16
Not used in regression
Temperature (°C)
Volume %
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900
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2.0
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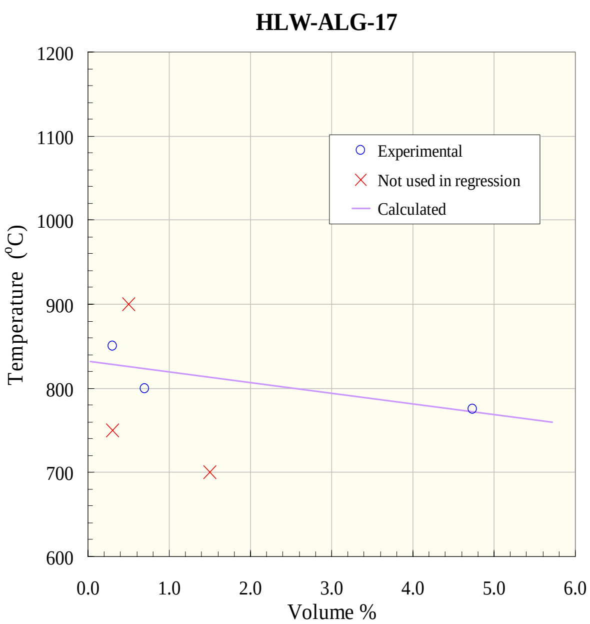
4.0
5.0
6.0


HLW-ALG-17
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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1000
900
800
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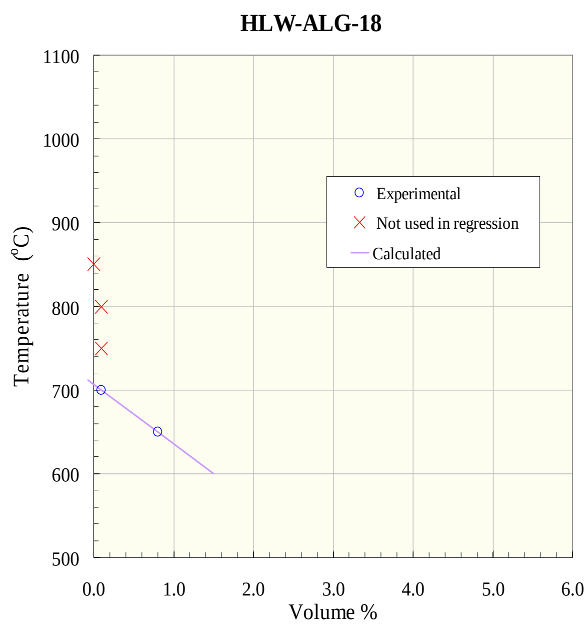
1.0
2.0
3.0
4.0
5.0
6.0


HLW-ALG-18
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
1100
1000
900
800
700
600
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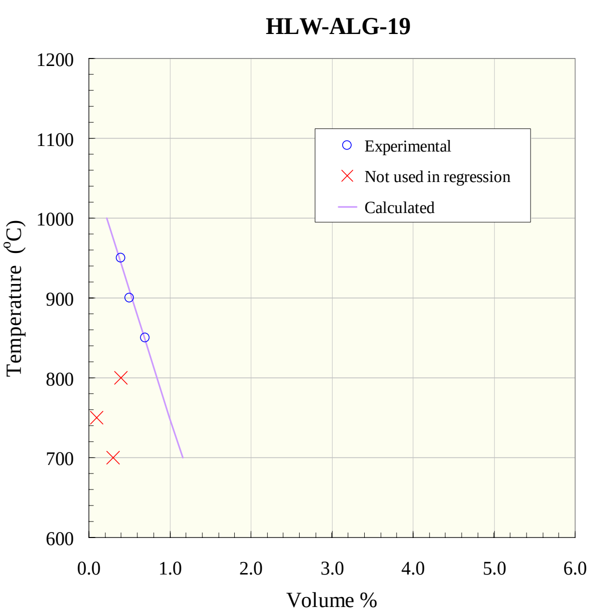
2.0
3.0
4.0
5.0
6.0


HLW-ALG-19
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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900
800
700
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1.0
2.0
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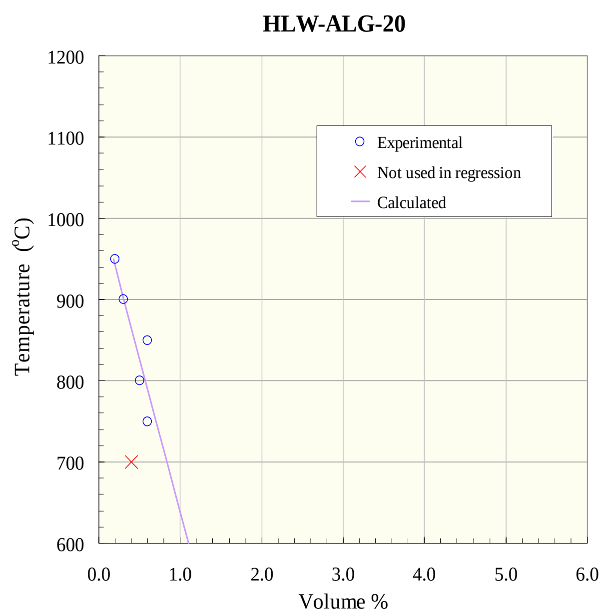
4.0
5.0
6.0


HLW-ALG-20
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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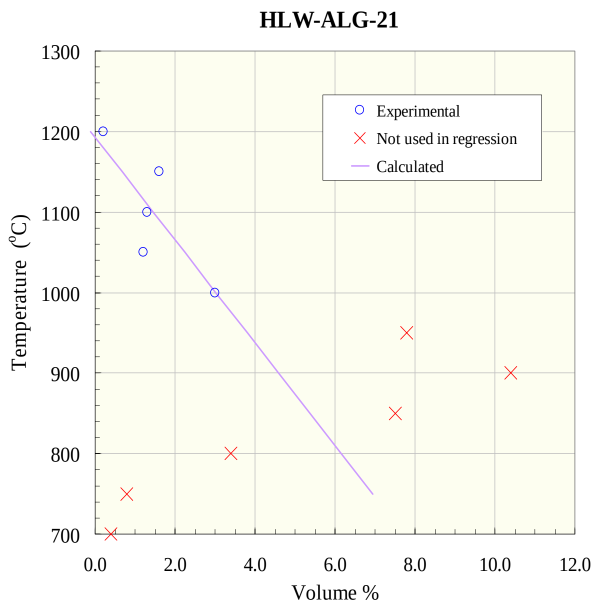
6.0


HLW-ALG-21
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
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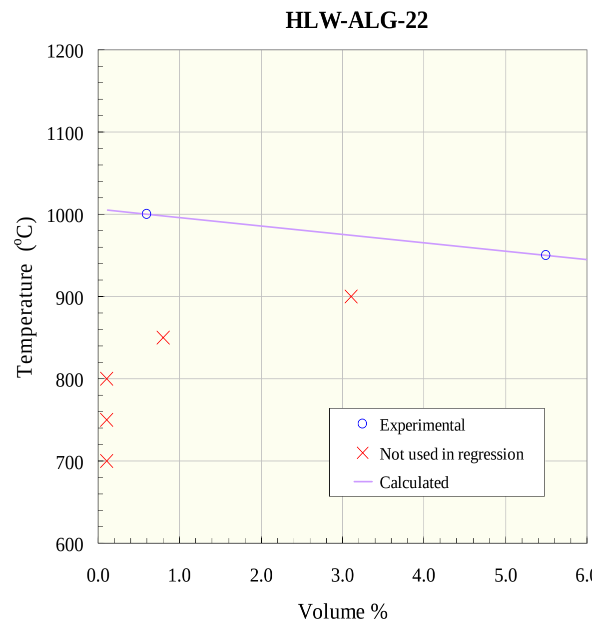
4.0
6.0
8.0
10.0
12.0


HLW-ALG-22
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
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1000
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700
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1.0
2.0
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4.0
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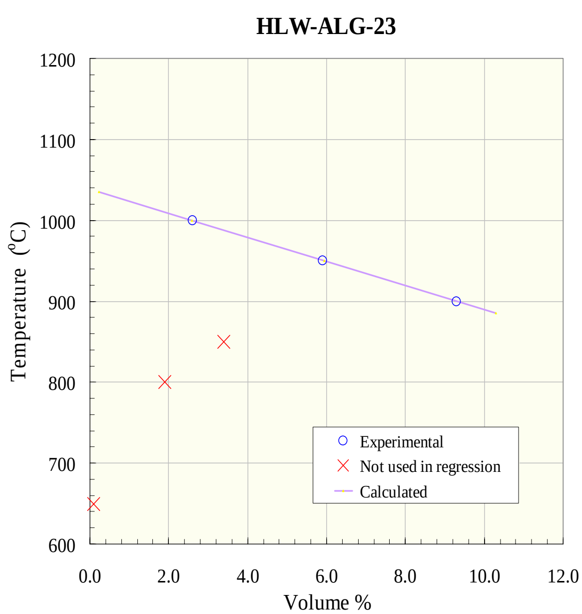
6.0


HLW-ALG-23
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
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800
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2.0
4.0
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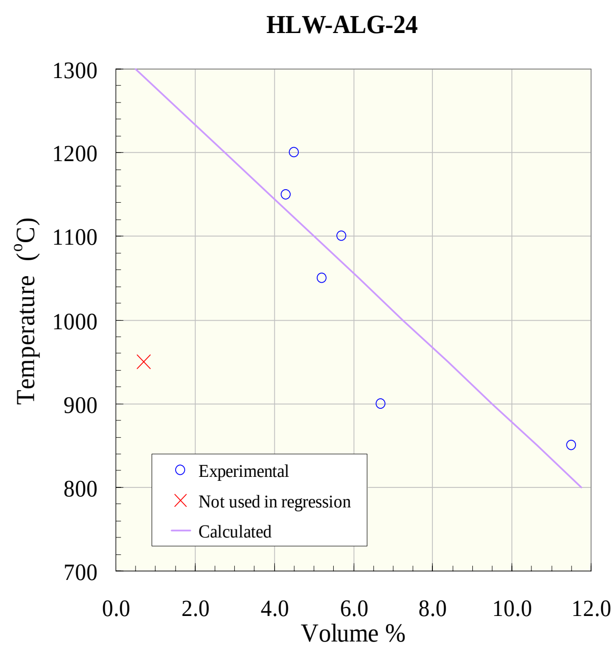
8.0
10.0
12.0


HLW-ALG-24
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
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1000
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2.0
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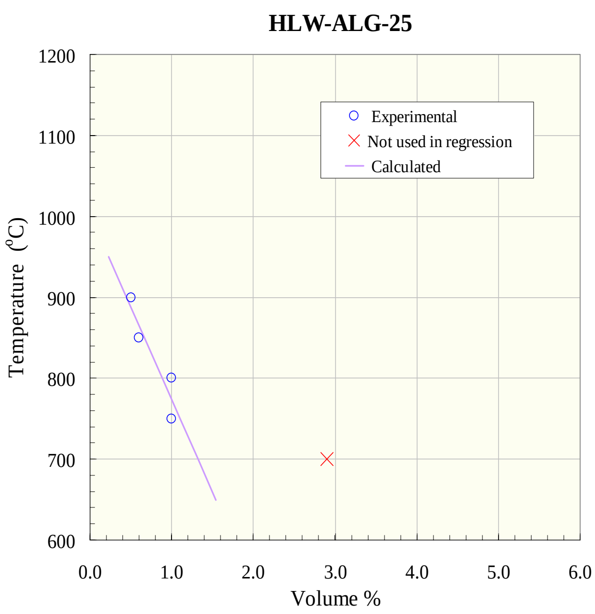
8.0
10.0
12.0


HLW-ALG-25
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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700
800
900
1000
1100
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2.0
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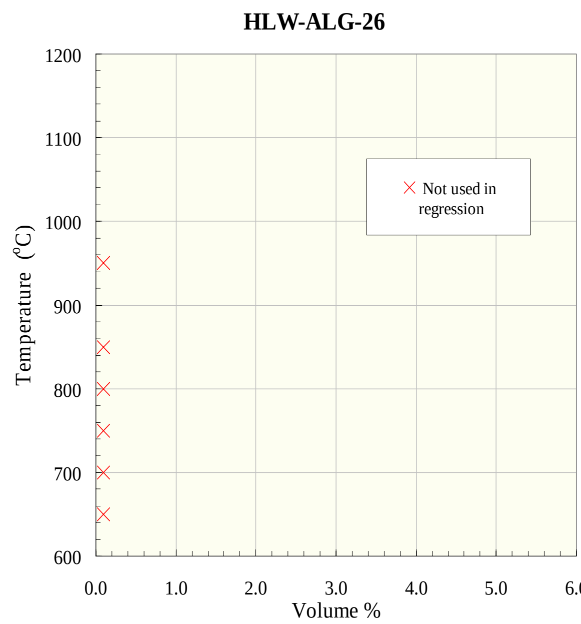
6.0


HLW-ALG-26
Not used in regression
Temperature (°C)
Volume %
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900
1000
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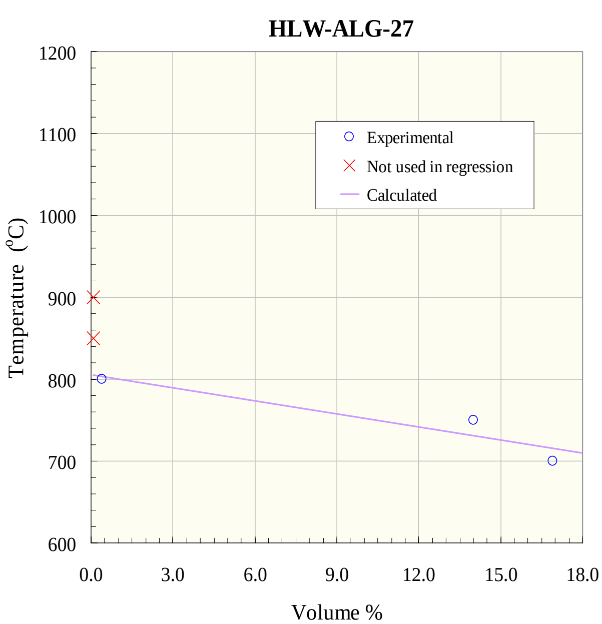
6.0


HLW-ALG-27
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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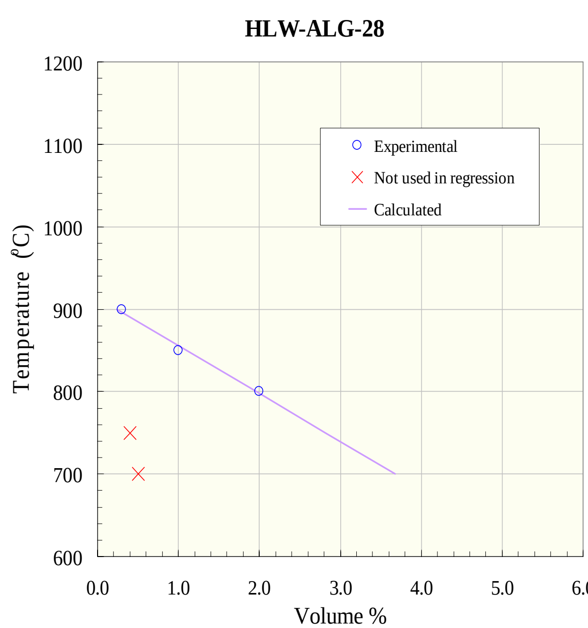
HLW-ALG-28
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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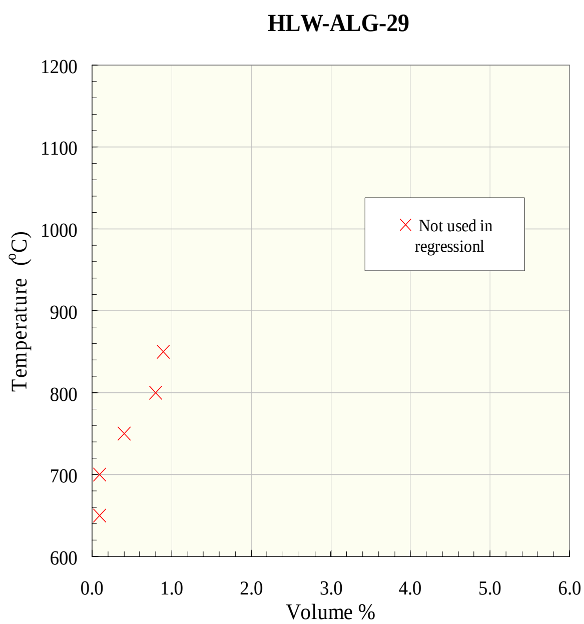
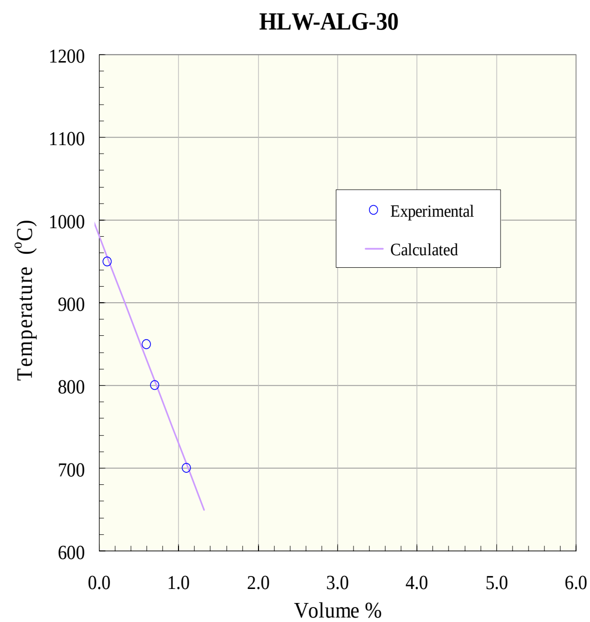
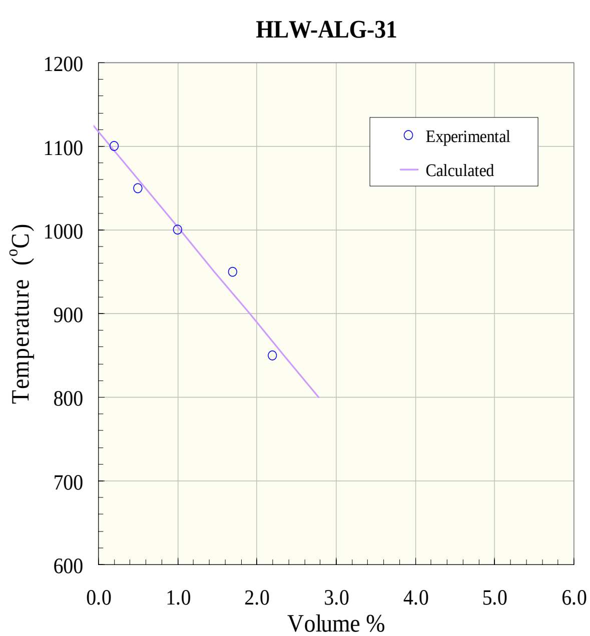
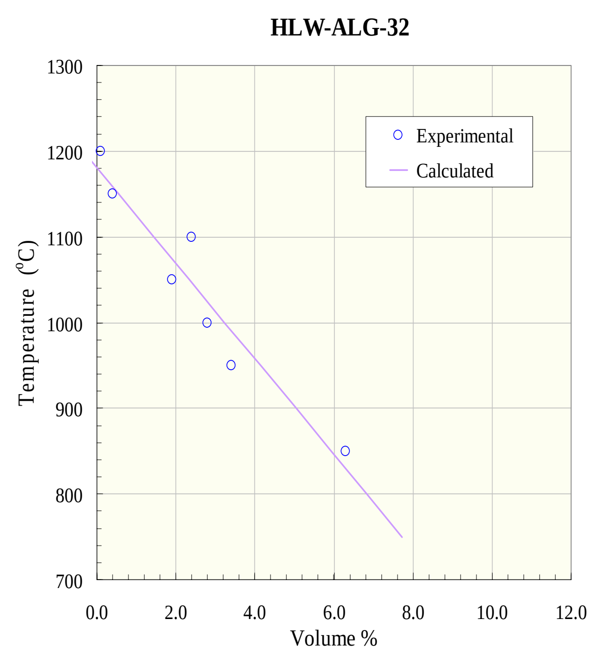
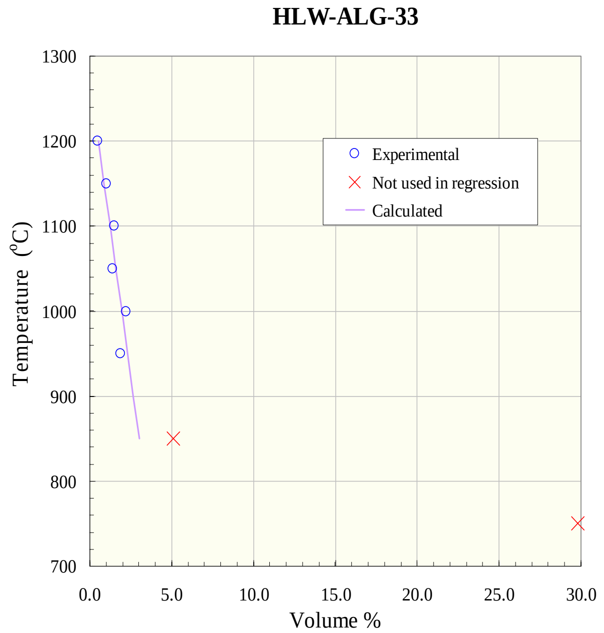
6.0


HLW-ALG-29
Temperature (°C)
Volume %
Not used in regressionl


HLW-ALG-30
Temperature (°C)
Volume %
Experimental
Calculated


HLW-ALG-31
Temperature (°C)
Volume %
Experimental
Calculated


HLW-ALG-32
Temperature (°C)
Volume %
Experimental
Calculated


HLW-ALG-33
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
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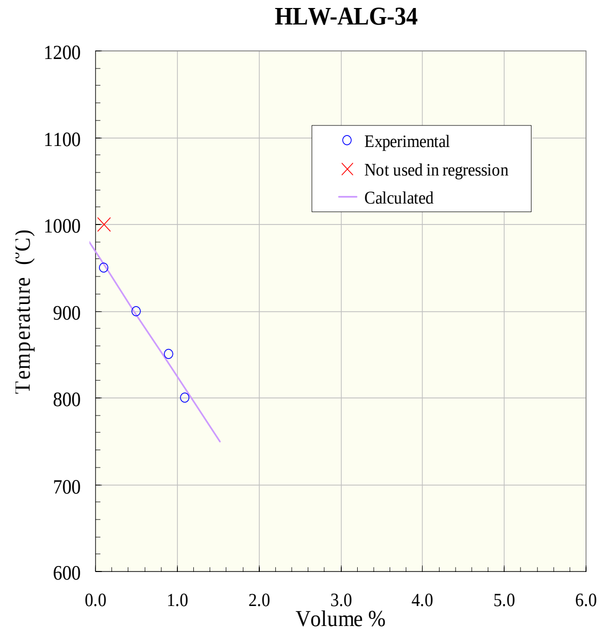
HLW-ALG-34
Temperature (°C)
Volume %
Experimental
Not used in regression
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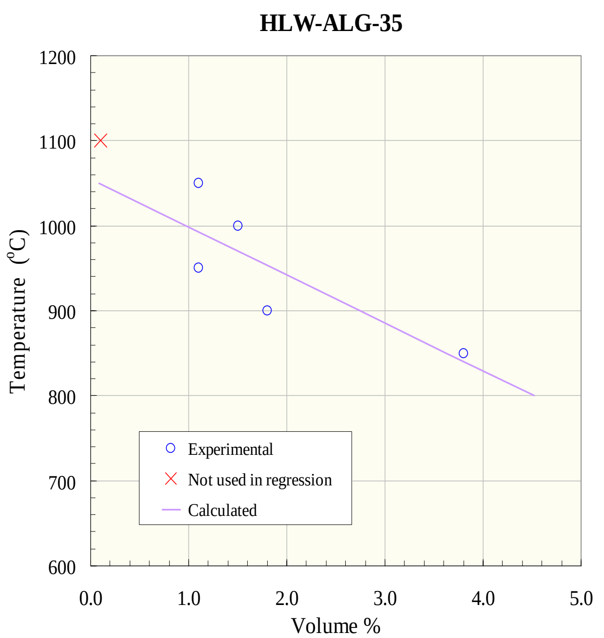
HLW-ALG-35
Temperature (°C)
Volume %
Experimental
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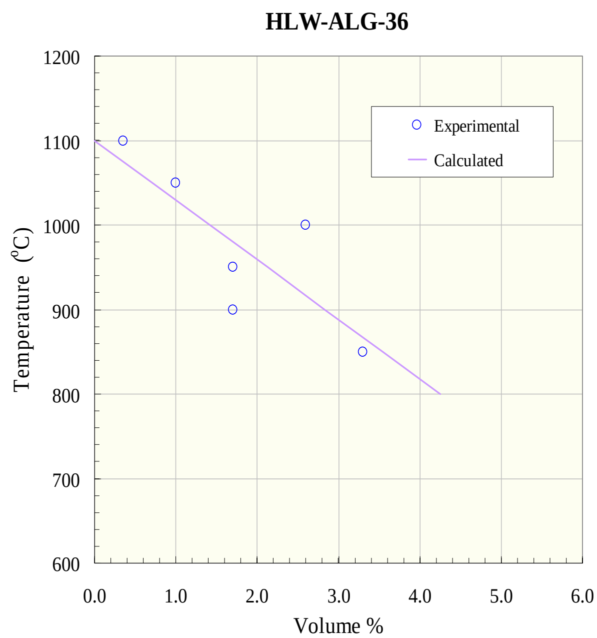
HLW-ALG-36
Temperature (°C)
Volume %
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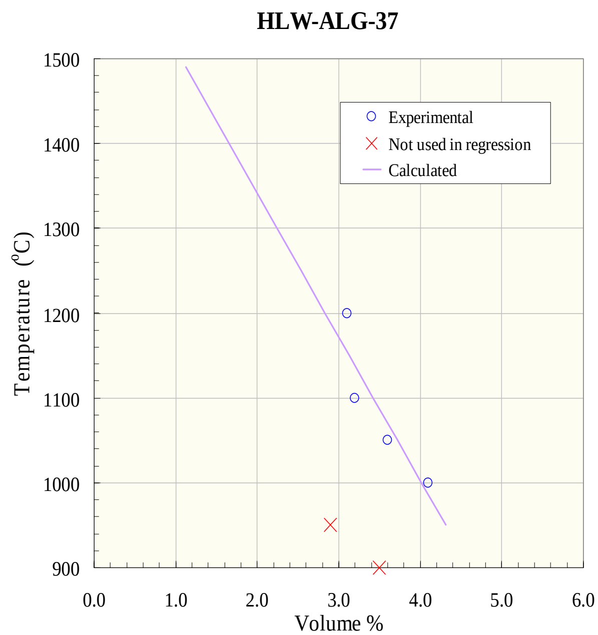
HLW-ALG-37
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
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1300
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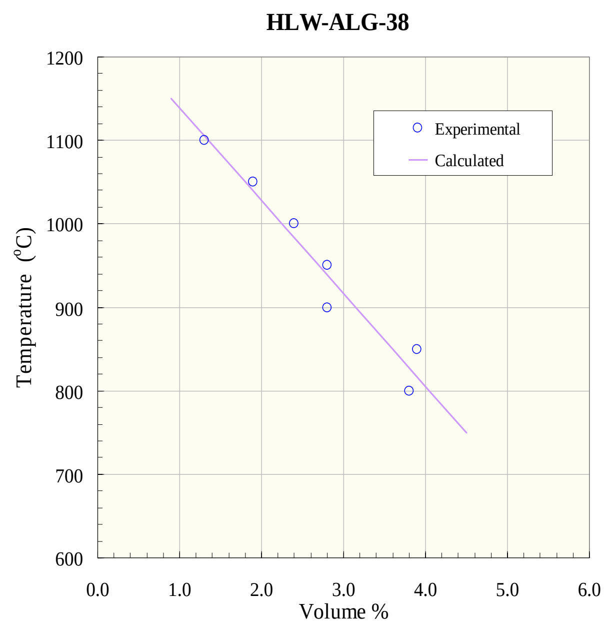
6.0


HLW-ALG-38
Experimental
Calculated
Temperature (°C)
Volume %
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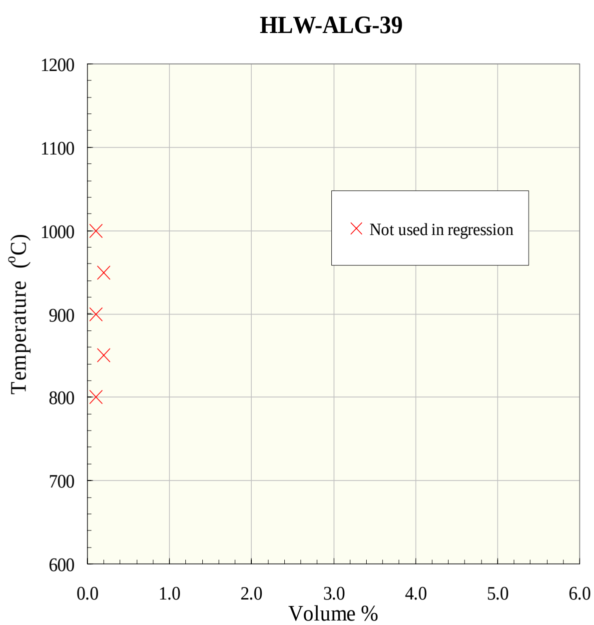
6.0


HLW-ALG-39
Not used in regression
Temperature (°C)
Volume %
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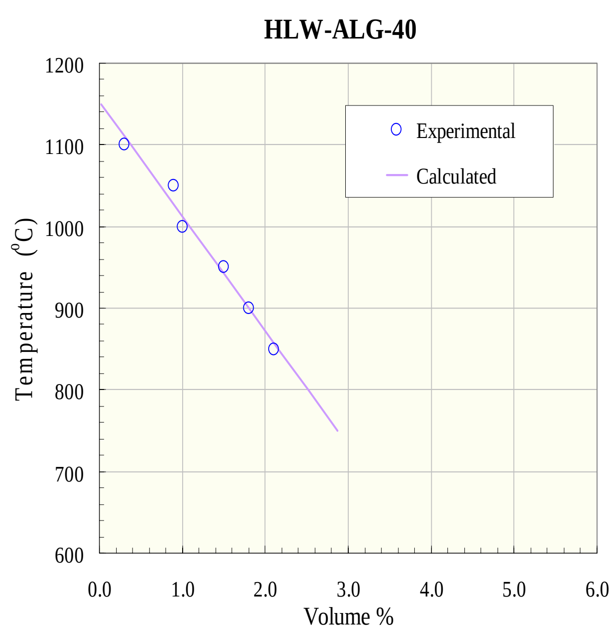
HLW-ALG-40
Experimental
Calculated
Temperature (°C)
Volume %
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1000
900
800
700
600
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1.0
2.0
3.0
4.0
5.0
6.0

R&T Technology Issues Summary

Test Report Title: Preparation & Testing of HLW Glasses to Support Development of WTP IHLW Formulation Algorithm

Test Report Number: VSL-06R1240-1, Rev 0

Prepared By: Keith H. Abel **Date:** December 18, 2006

Signature: [signature] 12/18/2006

Does the Testing or Report reveal any new discoveries, technology issues, or suggest potential follow-on work? **Yes** ☒ **No** ☐

If yes, describe the suggested activity.

The report describes formulation and testing of IHLW glasses that were specified by the initial or preliminary version of the WTP IHLW formulation algorithm. The current work was intended to aid in further development of the formulation algorithm not to validate a fully developed calculational methodology. The work was planned to "test" the algorithm at compositional HLW waste extremes and then examine whether the properties for glasses specified by the algorithm at these "challenging" extremes matched algorithm predicted properties. In many instances, approximately half, the glasses had at least one physical property, e.g., PCT release, viscosity, electrical conductivity, or T1%, that feel outside the region of production acceptability, i.e., the glass failed the constraint. The results of the property testing for the algorithm glasses produced and the property versus composition results from other HLW glasses developed using statistical design software, and reported separately in VSL-06R6780-2, will be used to improve the HLW glass property composition models. The improved models will then be incorporated into an updated version of the HLW processing algorithm. Further testing and validation of the updated algorithm is planned using HLW waste compositions provided at a time closer to actual WTP operations and thus the waste compostions will be more representative of actual wastes for processing within the HLW vitrification facility.

If appropriate, is a Request for Technology Development attached. **Yes** ☐ **No** ☒

Additional comments (include researcher recommendations):

R&T Subcontractor Document Review Record

1) To Be Completed by Cognizant R&T Personnel		
Document Number VSL-06R1240-1	Revision 0	Document Title Preparation & Testing of HLW Glasses to Support Development of WTP IHLW Formulation Algorithm
Test Spec: 24590-HLW-TSP-RT-01-006, Rev 1		Scoping Statement(s): VSL-13:HLW Glass Property Composition Modeling VSL-14:HLW Processing Properties Models

R&T Contact:	Keith Abel	MS6-N1	509-371-5847	October 31, 2006
	Name (Print)	MSIN	Telephone Number	Date

Review Distribution

Organization	Contact	MSIN	Required?
√ Process Engineering	T Valenti	MS4-C1	Yes ☒ No ☐
√ Quality Assurance	M Mitchell	MS14-4A	Yes ☐ No ☒
√ Environmental and Nuclear Safety	E&NS Doc Rev	MS4-D2	Yes ☒ No ☐
Commissioning and Training	S Gourley	MS12-B	Yes ☐ No ☒
√ Engineering	M Ongpin	MS4-A2	Yes ☒ No ☐
√ R&T Functional Manager	S Barnes	MS6-P1	Yes ☒ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐

Comments Due By: November 14, 2006

Required Reviewers are required to respond to the R&T Contact.

2) To be Completed by Reviewer

Reviewer __________ __________ __________

Name (Print) Organization Date

☐ Accepted, No Comments	☐ Accepted, Comments Not Significant	☐ Significant Comments, Form 24590-MGT-F00006 Attached	☐ Significant Comments, Comments Marked on Document

3) To be Completed by Reviewer*

My significant comments have been addressed.

Acceptance: __________ __________ __________

Print/Type Name *Signature* *Date*

** An e-mail to the R&T contact stating that significant comments are addressed can substitute for this acceptance.*

Abel, Keith H.

From: Valenti, Thomas
Sent: Thursday, December 07, 2006 10:44 AM
To: Abel, Keith H.
Subject: RE: Comment Responses for HLW Algorithm Data Report, VSL-06R1240-1

Responses to Process Engineering and Engineering comments are accepted. Request to proceed to the Rev 0 report is also accepted.

Thomas J. Valenti

Process Engineering Group
MPF C120A
509/ 371-3760

-----Original Message-----
From: Abel, Keith H.
Sent: Tuesday, December 05, 2006 7:22 AM
To: Lee, Ernest D (WTP); Gimpel, Rod
Cc: Valenti, Thomas
Subject: Comment Responses for HLW Algorithm Data Report, VSL-06R1240-1

Ernie, Rod, and Tom,

Attached are the responses to your comments on the report. Please review and let me know if the responses are adequate to resolve your comments and that we should incorporate and proceed to the rev 0.

Thanks,

Keith

<< File: Resp HLW Alg Glass Data Rept 1105-EngPE Comments.doc >>

Abel, Keith H.

From: Valenti, Thomas
Sent: Thursday, December 07, 2006 10:44 AM
To: Abel, Keith H.; Gimpel, Rod
Subject: RE: Comment Resolution for HLW Algorithm Glass Data Report, VSL-06R1240-1

I have Rod's acceptance and am preparing the PE/ Eng acceptance statement.

Thomas J. Valenti

Process Engineering Group
MPF C120A
509/ 371-3760

-----Original Message-----
From: Abel, Keith H.
Sent: Thursday, December 07, 2006 10:42 AM
To: Gimpel, Rod
Cc: Valenti, Thomas
Subject: RE: Comment Resolution for HLW Algorithm Glass Data Report, VSL-06R1240-1

Rod,

Ernie has now accepted the authors responses. Please notify Tom that you also accept the VSL responses so he can provide final Engineering documentation to me.

Thanks,

Keith

-----Original Message-----
From: Lee, Ernest D (WTP)
Sent: Thursday, December 07, 2006 10:36 AM
To: Valenti, Thomas
Cc: Abel, Keith H.; Gimpel, Rod
Subject: Comment Resolution for HLW Algorithm Glass Data Report, VSL-06R1240-1

Tom,

I have closed with Keith. He assures me the change of concern has been accepted and will be fixed in the final report. Therefore, I am ready to state that my comments are resolved.

Thank you

Ernie

Abel, Keith H.

From: Lee, Ernest D (WTP)
Sent: Thursday, December 07, 2006 10:36 AM
To: Valenti, Thomas
Cc: Abel, Keith H.; Gimpel, Rod
Subject: Comment Resolution for HLW Algorithm Glass Data Report, VSL-06R1240-1

Tom,

I have closed with Keith. He assures me the change of concern has been accepted and will be fixed in the final report. Therefore, I am ready to state that my comments are resolved.

Thank you

Ernie

Abel, Keith H.

From: Gimpel, Rod
Sent: Thursday, December 07, 2006 7:15 AM
To: Abel, Keith H.
Subject: RE: Comment Responses for HLW Algorithm Data Report, VSL-06R1240-1

Keith, the comment resolutions look good. Have a great day.

Thanks,

Rod

-----Original Message-----
From: **Abel, Keith H.**
Sent: Tuesday, December 05, 2006 7:22 AM
To: Lee, Ernest D (WTP); Gimpel, Rod
Cc: Valenti, Thomas
Subject: Comment Responses for HLW Algorithm Data Report, VSL-06R1240-1

Ernie, Rod, and Tom,

Attached are the responses to your comments on the report. Please review and let me know if the responses are adequate to resolve your comments and that we should incorporate and proceed to the rev 0.

Thanks,

Keith

<< File: Resp HLW Alg Glass Data Rept 1105-EngPE Comments.doc >>

Abel, Keith H.

From: Abel, Keith H.
Sent: Wednesday, December 06, 2006 9:04 AM
To: Lee, Ernest D (WTP)
Cc: Valenti, Thomas
Subject: Lee questions RE: Comment Responses for HLW Algorithm Data Report, VSL-06R1240-1

Importance: High

Ernie,

Regarding Comment #2:

Here is my interpretation. The definition of "verify" in Merriam Webster is "to establish the truth, accuracy, or reality of" . The definition to me also means that if un-true, un-accurate, or un-real, that should is also determined. VSL did that in the current test program. They did perform a verification of the acceptability of the glasses. The verification of the algorithm confirmed the glasses would not be acceptable for production. We knew going in that the algorithm is not mature, i.e., the accuracy of the algorithm in its current state, known to be preliminary was previously untested with real glasses. As we discussed in Vijay's office, we also designed the testing program exercising the algorithm to the "outer edges" of the constraint limits and in hindsight beyond its limits.

Regarding Comment #5:

We are doing so. In fact, we have delayed certain HLW glass work at the subcontractor pending review of the TFCOUP Rev 6. Action is being taken addressing the concern expressed in your comment.

I hope this addresses your concern adequately. The above information will be part of the documentation package that goes into PDC for the document. So this discussion will be documented for the record.

Keith

-----Original Message-----
From: Lee, Ernest D (WTP)
Sent: Wednesday, December 06, 2006 8:34 AM
To: Abel, Keith H.
Cc: Valenti, Thomas
Subject: RE: Comment Responses for HLW Algorithm Data Report, VSL-06R1240-1

Keith,

Ok with response to no 1.
Not OK with response to no 2. The definition of "verify" - is to confirm or substantiate
Clearly the results of this study does NOT confirm or substantiate the acceptability of glass made
using the algorithm
Please have someone in R&T address comment 3
OK with response to no 4
Please have someone in R&T Address comment 5, it appears DOE has assign this work to CHG

-----Original Message-----
From: Abel, Keith H.
Sent: Tuesday, December 05, 2006 7:22 AM
To: Lee, Ernest D (WTP); Gimpel, Rod
Cc: Valenti, Thomas
Subject: Comment Responses for HLW Algorithm Data Report, VSL-06R1240-1

Ernie, Rod, and Tom,

Attached are the responses to your comments on the report. Please review and let me know if the responses are adequate to resolve your comments and that we should incorporate and proceed to the rev 0.

Thanks,

Keith

<< File: Resp HLW Alg Glass Data Rept 1105-EngPE Comments.doc >>

COMMENT RESOLUTION FORM

Return to: Keith Abel

Comments Due: November 14, 2006

Document Title: Preparation & Testing of HLW Glasses to Support Development of WTP IHLW Formulation Algorithm	Document No. VSL-06R1240-1	Revision: 0	Date: October 31, 2006
Reviewer: Ernie Lee (EL), Rod Gimpel (RG) Date: 11/15/2006	Response by: Date:	Comments Resolved: Date:	

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
1 (EL)	General	The way the information is presented in this report, will likely result in sending an unintended message. After discussing the issues with R&T, I am no longer as concerned about the report results. However, to prevent others from over-reacting as I did, it is strongly recommended to make major changes the Summary of TESTING; Section 1, Introduction; Section 4, Results and Discussion; and Section 5, Summary and conclusions. What would help, would be to discuss or show graphically up front, that the IHLW formulation algorithm applicability constraints were <u>not</u> utilized when formulating the 100 glasses and the 40 glass subset that were actually tested and reported on.	M	If changes are not made the reader will conclude that all the current HLW glass property models are highly deficient and perhaps there is a significant risk that the use of a model for calculating glass formulation will product unacceptable IHLW.	Changes will be made as suggested to emphasize throughout the text that the IHLW formulation algorithm is preliminary and that it will be refined with data already collected and future updates of property-composition models. As suggested, discussion will be added to indicate that many of the glasses calculated and tested are compositionally outside the validity ranges for the models used. Further, glasses that do not meet the $T_{1\%}$ constraints due to crystallization of Zr- and Th-containing phases will be identified (see response to item 6), further demonstrating that the "applicability constraints" were not applied.	
2 (EL)	Summary of Testing Table, pg 7	The Test objectives in this table must be changed. As I understand the test objective, after a discussion with R&T. The objective was	M	The objective as written is "Verify the acceptability of the glass compositions formulated by the preliminary glass formulation algorithm"	The objective stated in the report is to establish whether or not the algorithm glasses are acceptable for production, which has been achieved by collecting the	

COMMENT RESOLUTION FORM

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
		not to verify the acceptability of the glass composition formulated by the preliminary glass formulation algorithm. Rather, the real objective was to determine what are the boundaries that the current Preliminary glass formulation would exceed could result in failed glass. An additional objective was to identify what additional glass to added to the glass property models. As written, one would conclude that none of the test objectives were achieved.		-Failed Clearly when 20 of 40 glasses specified by the glass formulation algorithm failed, the glass formulation algorithm is not acceptable!	appropriate data and showing which of the constraints are met or exceeded. Further, the objective is a direct quote from the algorithm test guidance. We are concerned that one of the purposes of controlling documents, and a requirement in the reports, is to assess results against pre-stated objectives. Consequently, re-stating objectives after the fact seems problematic. Instead, we will make changes to emphasize the fact that this is a preliminary algorithm and data will be used to refine it and the glass property-composition models that support it (see response to item #1).	
3 (EL)	General	This report should not be considered to be a final report. When a report is marked "final", it causes the report to be reconciled. This report should be listed either as an Interim Report or a statement added "Report not approved for Project Use"	M	Results from this work should not be used directly by the project for making any changes to the design or flowsheet models.	This report documents the results from testing designed to support the development of the IHLW formulation algorithm. The algorithm is preliminary in nature but the test results are not. Once the report goes through the review/approval process, and WTP R&T approves it, our understanding is that the report will be released for Project use. It is up to WTP R&T to provide guidance on how the results in the report should be used.	

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
4 (EL)	Section 5	This section should include a more detailed description of the path forward to correct all the problems identified with the existing glass property models.	M	Conclusions need to be expanded	Section 5 will be expanded, not only to stress the fact that the formulation algorithm is preliminary, but also to include a description of the follow-up work that is designed to improve upon the algorithm, which is part of the overall objective of this work (page 15, last paragraph of Section 1.1).	
5 (EL)	General	It is recommended that R&T consider changing the present work schedule. As I understand the present plan is to use the information from this report and other existing glasses to update the glass property models and the IHLW Formulation Algorithm now. However, the project knows that the current glasses do not cover the known ranges of feeds planned for the WTP mission (e.g., high Bi, Hi P, higher chromium and sulfate feeds). It would seem prudent to hold off in developing new models until glasses are developed for the other known feed types that WTP are expected to receive. Then develop the glass property models. If not, all this coming work will be repeated and little value will be obtained by updating the models.	M	Waste of ORP and WTP resources to continue as planned. Since the presently planned work is an expansion of the current contract requirements (more than 4 HLW batches), why do anything more. Lets to the needed work or none.	This is a programmatic question for WTP R&T.	
6 (RG)	Summary and General	Make an extra set of charts. The extra set should be populated only with those glasses whose compositions are within the valid range of the models. This would give some credence to the summary statement that validity ranges of the models need to be	M	The extra charts are needed to see if the existing models work if used in valid ranges.	Existing figures in the report will be revised to distinguish glasses that are compositionally inside the validity ranges of the models from those that are outside. This is similar to Figure 4.8, where	

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[b]	Response	Resolution
		expanded. If the models still don't predict these glasses well, then the problem is more serious that just the validity range of the models.			glasses that exceed the $T_{1\%}$ constraint limit but with non-spinel major phases were identified. A cursory review of the data shows that a vast majority of the glasses that do not meet the constraint requirements are either outside the validity ranges or crystallize Zr- and Th-containing phases (no models were used in the formulation algorithm to limit formation of those phases).	
7 (RG)	Target Composition Table	State the Waste Loading Constraint that is being met for each glass and by how much.	I		A comparison of Tables 2.3 and 2.8 will show which of the waste loading constraints is met. The waste loading factor found in Table 2.7 indicates for each glass the fraction of the minimum required waste loading. We will add to Table 2.8 identification of which waste loading constraint has been met by each of the glasses.	
8 (RG)	Target Composition Tables	There are numerous charts with various data on each. This makes it hard to keep track which glass passed or failed and for what reason. Consider placing the measured properties on the bottom of each target composition. This would make the font of these charts a little smaller but the charts would be more meaningful.	I		Table 4.3 already provides a concise summary of the important properties measured. It also clearly identifies the glasses that do not meet all constraints and which of the constraints are exceeded.	

[a] **Significance**: M = Mandatory; I = Improvement. Definitions for these terms are provided at the end of the form instructions and in Appendix B of procedure "WTP Document Administration".
[b] Justification required for Mandatory Comments.

Abel, Keith H.

From: Reed, Ronald D (WTP)
Sent: Tuesday, December 05, 2006 12:26 PM
To: Abel, Keith H.
Cc: Mitchell, Michelle
Subject: RE: Comment Response on HLW Algorithm Data Report, VSL-06R1240-1

Keith -

My significant comments have been addressed.

Ronald D. Reed/QA

-----Original Message-----
From: Abel, Keith H.
Sent: Tuesday, December 05, 2006 7:18 AM
To: Reed, Ronald D (WTP)
Subject: Comment Response on HLW Algorithm Data Report, VSL-06R1240-1

Ron,

Attached is the response to your comment on the report. Please review and let me know if the response is adequate to resolve your comment and that we should incorporate and proceed to the rev 0.

Thanks,

Keith

<< File: Resp CRF HLW Alg Glass Data Rept RReed.doc >>

COMMENT RESOLUTION FORM

Return to: Keith Abel

Comments Due: November 14, 2006

Document Title: Preparation & Testing of HLW Glasses to Support Development of WTP IHLW Formulation Algorithm	Document No. VSL-06R1240-1	Revision: 0	Date: October 31, 2006
Reviewer: Ron Reed — Date: 11/13/06	Response by: — Date:	Comments Resolved: — Date:	

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
1	Page 9 and 31:	• The Quality Assurance Sections cite PL-24590-QA00001, QAPjP for Testing Program Generating Environmental Regulatory Data, which is referenced in the Test Specification, 24590-HLW-TSP-RT-01-006, quality assurance section. *NOTE by Keith! I talked to Ron on the telephone on 11/13/06 at 2:10 PM.* *Ron's concern is that the Test Specification QA requirements include the QAPjP for TCLP work. We need to make a statement that the QAPjP does not apply to the algorithm data report since TCLP testing was not conducted.* Keith -	M		Statement will be made as suggested in the appropriate sections.	

COMMENT RESOLUTION FORM

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[b]	Response	Resolution

[a] **Significance**: M = Mandatory; I = Improvement. Definitions for these terms are provided at the end of the form instructions and in Appendix B of procedure "WTP Document Administration".

[b] Justification required for Mandatory Comments.

Abel, Keith H.

From: Blumenkranz, David
Sent: Wednesday, December 06, 2006 7:40 AM
To: Abel, Keith H.
Subject: RE: Comment Responses for HLW Algorithm Data Report, VSL-06R1240-1

Looks Great. I concur with the responses.

-----Original Message-----
From: Abel, Keith H.
Sent: Tuesday, December 05, 2006 7:21 AM
To: Blumenkranz, David
Subject: Comment Responses for HLW Algorithm Data Report, VSL-06R1240-1

Dave,

Attached are the responses to your comments on the report. Please review and let me know if the responses are adequate to resolve your comments and that we should incorporate and proceed to the rev 0.

Thanks,

Keith

<< File: Resp CRF HLW Alg Glass Rpt DBBrvw.doc >>

COMMENT RESOLUTION FORM

Return to: Keith Abel

Comments Due: November 14, 2006

Document Title: Preparation & Testing of HLW Glasses to Support Development of WTP IHLW Formulation Algorithm	Document No. VSL-06R1240-1	Revision: 0	Date: October 31, 2006
Reviewer: David Blumenkranz Date: 11/13/06	Response by: Date:	Comments Resolved: Date:	

Item No.	Section/ Paragraph	Comment	Signif-icance[a]	"M" Comment Justification[B]	Response	Resolution
1.	Summary part A, last ¶, 3rd sent.	Revise to read, "The TCLP models and associated data are the subjects of a separate report [10]~~that is being used to support a petition to delist IHLW glasses~~."	M	Avoid reference to the petition in this technical report. The adequacy of the TCLP-model and the expanded composition range has not been assessed. It should not be implied that the petition or existing TCLP-model are currently adequate for the compositions described in this report.	Revision will be made as suggested to remove all references to the petitions. See also response to item #6.	
2.	Summary part A, last ¶, 3rd sent.	State that the scope of testing and subsequent data analysis in this report does not include TCLP-model development work or assessment of existing TCLP-model adequacy for the glass compositions that were tested to support algorithm development/revision.	M	It should not be implied that the petition or existing TCLP-model are currently adequate for the compositions described in this report.	Additional text will be included to clarify the scope of testing and analyses covered in this report.	
3.	Summary part C, last ¶, last sent.	Provide a reference that documents the nepheline formation issue (for traceability).	I		The results of the *present* work showed nepheline formation upon CCC heat treatment of some algorithm glasses and its impact on PCT releases.(Section 4.5). There is no prior reference for these glasses. Based on these results, it is recommended that a	

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
					constraint be included in the algorithm to limit its formation (Sections 4.5 and 5).	
4.	Summary part D and § 6	State that since TCLP was not within scope, the QAPjP did not apply.	I		Statement will be added as suggested in the appropriate sections.	
5.	Summary part E	Cite the source for the algorithm used in the design of the work described in this report.	M	With time, the algorithm will be updated, so it is important to keep track of which version of the algorithm was used in planning this work.	A determination will be made on the source/version of the algorithm used and the information will be added in the report.	
6.	§ 1, 3rd bullet (TCLP)	The explanation provided is incorrect. Starting at the fourth sentence, please revise as follows; "The current testing, however, did not include TCLP. The WTP project has elected to defer TCLP testing and corresponding related updates to the IHLW algorithm because it is not cost effective at this time. Current data indicate that TCLP is one of the least restrictive constraints, thus, a graded approach to IHLW algorithm development is being implemented for TCLP. Once the acceptable composition range has been adequately defined by other constraints (e.g. $T_{1\%}$, PCT, conductivity, etc.), additional testing for TCLP response can be initiated. Such testing, and a corresponding revision of the TCLP cadmium release model and IHLW algorithm will be required if the WTP processes feeds outside of the composition range described by the current version of the TCLP model. ~~because of the petitions for Variance to Land Disposal Restriction (LDR) and for Waste Delisting. If successful, the LDR Variance will be technology-based with the only restriction that the waste be treated by vitrification [11]. For the delisting petition [12], two conditions on the waste form must be met: (i) the average mass fraction of Tl2O in each waste batch must be ≤ 0.00465, and (ii) the average mass fraction of CdO in each waste batch must be ≤ 0.001 or the calculated TCLP release of cadmium (plus~~	M	The conditions proposed in the delisting petition are only applicable to the range of glass compositions tested (e.g. compositions related to AZ-101, AZ-102, AY-102/C-106 and AY-101/C-104). There is a high probability that additional TCLP work will be required prior to processing other tank waste. To save the client money (defer costs until later in light of the current political atmosphere), WTP recommended deferral of such testing until more definitive information on the impact of other property constraints and potential feed compositions was	Revision will be made as suggested. The associated reference will also be removed.	

COMMENT RESOLUTION FORM

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
		~~uncertainty) must be ≤ 0.48 mg/l using the TCLP model developed. When both conditions are met, the waste form will meet the required specifications with no further testing required.~~" Remove references [11] and [12].		known better.		
7.	§ 2, 1st ¶, 2nd sent.	Please clarify what is meant by "the composition is optimized for a series of target component concentrations and property values."	I		The sentence will be rewritten as "In cases where multiple glass compositions can meet all constraints, the composition is optimized to increase the robustness of the process and to lower the risk of processing difficulties (e.g., it is advantageous to process some distance from rather than too close to any one property limit)."	
8.	§ 2, 3rd ¶, 1st bullet	Why look at different vessel contents for the different G2 run? Why remove the heel from the MFPV? Please clarify	I		To implement the IHLW formulation algorithm during the WTP operation, several steps are envisioned that may include sampling and analyses of materials from different vessels. Various waste sources, including made-up wastes, were examined during the initial development of the algorithm. The text states that contribution from the glass forming chemicals (GFC) in MFPV heels were removed, not the heel itself, in arriving at the waste compositions.	
9.	§ 4.5	Is the presence of nepheline also likely to impact TCLP response? Please address this possibility.	M	Future planning.	Formation of nepheline affects chemical durability of the glass and is likely to impact TCLP	

Item No.	Section/ Paragraph	Comment	Signif-icance[a]	"M" Comment Justification[B]	Response	Resolution
					response as well as PCT response. It is therefore a conclusion of this report that additional constraints be used to limit its formation.	
10.	Table 4.2	Use mg/L instead of ppm for clarity.	I		The unit ppm was used to maintain consistency with previous reports that described testing performed to support PCT modeling.	
11.	Figures 4.1, 4.2, 4.3, 4.8	The plots should show the uncertainty portion of the predicted values as a bracket/bar as was done for Figure 4.4. Likewise, the experimental data should also show error bars approximating its uncertainty (approximated from duplicate measurements). As currently, shown, the graphs are deceiving because the plotted model predictions really represent an upper threshold, not the range of model accuracy.	I		Calculated values for all glass properties were provided by the WTP, with uncertainties included only for the viscosity at 1150°C, which were plotted in Figure 4.4. If uncertainties for the other properties are available, we will include them in the other figures. Although the axes in the figures are appropriately labeled to provide the accurate information, we will attempt to emphasize the exact nature of the data being plotted.	

[a] **Significance**: M = Mandatory; I = Improvement. Definitions for these terms are provided at the end of the form instructions and in Appendix B of procedure "WTP Document Administration".

[b] Justification required for Mandatory Comments.

Abel, Keith H.

From: Bostic, Lee
Sent: Tuesday, December 05, 2006 7:49 AM
To: Abel, Keith H.
Subject: RE: Comment Responses on HLW Algorithm Glass Data Report, VSL-06R1240-1

Keith,

Your response to my comment is acceptable. Please proceed to rev. 0.

Thanks,

Lee Bostic

-----Original Message-----
From: Abel, Keith H.
Sent: Tuesday, December 05, 2006 7:25 AM
To: Bostic, Lee
Subject: Comment Responses on HLW Algorithm Glass Data Report, VSL-06R1240-1

Lee,

Attached is the response to your comment on the report. Please review and let me know if the response is adequate to resolve your comment and that we should incorporate and proceed to the rev 0.

Thanks,

Keith

<< File: Resp CRF HLW Alg Glass Data Rept 1105 bostic.doc >>

COMMENT RESOLUTION FORM

Return to: Keith Abel | Comments Due: November 14, 2006

Document Title: Preparation & Testing of HLW Glasses to Support Development of WTP IHLW Formulation Algorithm	Document No. VSL-06R1240-1	Revision: 0	Date: October 31, 2006
Reviewer: Lee Bostic; Date: 11/15/06	Response by: Date:	Comments Resolved: Date:	

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
1	Pg 14	-, TCLP bullet. Perhaps the section means to say that the current testing did not include TCLP testing because the compositions are within the bounds already tested in reference [10]. The petitions themselves will not provide an escape from the requirement to develop an appropriate formulation that meets TCLP release limits. If work here changes the TCLP model coefficients used to provide the basis for the petitions, additional formulation development may be required. I would note that proposed condition of the delisting petition proposes using the formulation model developed to support the petition as a condition of petition approval. If the concentrations meet the mass fraction for Tl and Cd, are within the composition ranges previously tested (reference [10]) and the formulation meets the other TCLP model constraints, then no formulation work will be required. If not, then formulation model work could be required prior to processing.	Mandatory		In view of the comments of this and other reviewers, the report will be revised such that all references to the petitions will be removed. Instead, it will be stated that the WTP Project has elected to defer TCLP testing and associated updates to the IHLW formulation algorithm. Additional TCLP testing will be performed if the WTP processes wastes outside of the compositional range described by the current version of TCLP model.	

[a] **Significance**: M = Mandatory; I = Improvement. Definitions for these terms are provided at the end of the form instructions and in Appendix B of procedure "WTP Document Administration".

[b] Justification required for Mandatory Comments.

COMMENT RESOLUTION FORM

Return to: Keith Abel

Comments Due: November 14, 2006

Document Title: Preparation & Testing of HLW Glasses to Support Development of WTP IHLW Formulation Algorithm		Document No. VSL-06R1240-1		Revision: 0	Date: October 31, 2006
Reviewer: KeithAbel for Steven M Barnes	Date: 11/06/06	Response by:	Date:	Comments Resolved: [signature]	Date: 12/5/2006

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
1	C, page 9	Line 2 "and were, therefore, found not acceptable." Suggest changing to read "and would be, therefore, not acceptable for IHLW production." It also might be useful to state that the glasses beyond the constraint limit are quite useful, if not too far beyond the limit, for improving the property composition models. The word unacceptable conveys meaning that should be further explained, at least to this reviewer.	I		Per comments of other reviewers, the phrase "and were, therefore, found not acceptable" will be deleted. Suggested addition about usefulness of the data beyond constraint limits will be made. Emphasis will also be made, in this section and elsewhere, that the algorithm is preliminary and improvement will be made with the data collected.	KHA 12/5/2006
2	1.1, page 14	In the TCLP discussion, it would be useful to mention that archive glass is available for future TCLP testing, should it be needed. (Is this the case?) The petition may need to be revised if the composition region changes a great deal from that in the current petition.	I		Per comments of other reviewers, the bullet will be rewritten to remove all references to the petitions and to state that additional TCLP testing will be required should the WTP process wastes outside of the composition range defined by the current TCLP model. We will also state that archive glass samples, if available in sufficient amounts, will be used in future TCLP testing.	KHA 12/5/2006

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
3	Sec 2, line 1, page 17	Suggest changing "was" to "is being", since the current version of the algorithm is viewed as "preliminary" and the current data set will be used to improve models that are part of the algorithm, thus improving the algorithm.	I		Change will be made as suggested.	KHA 12/5/2006
4	Sec 2.2, last para on page 20, 10 lines from bottom	" but with reduced alkalis concentration".Either the s should be dropped and/or the wording should be "total alkali".	E		Will rewrite as "with reduced total alkali concentration,"	KHA 12/5/2006
5	4/3, page 28	Line 4 "did not meet the viscosity and PCT constraint limits". I suggest changing and to and/or, since only one glass did not meet the PCT constraint.	E		Change will be made as requested.	KHA 12/5/2006
6	References	Ref 8, The actual issue date (VSL/Duratek signatures) is November 7, not Nov. 8. Suspect the date should be changed.	E		The exact date of issue will be checked and the correct information will be used.	KHA 12/5/2006
7	Table 2.1	Constraint column, I think 3rd entry from bottom of table 1150 should be 1100. The text should explain why the entries are not ± for the viscosity and conductivity constraint entries. Also, the table might delete the limit that will not apply, e.g., the lower viscosity at 1100 C.	E I		Agreed. The correction from 1150 to 1100 will be made. Additional text will be added to describe the constraint limits. All constraints were provided in the test guidance by the WTP Project. They were included in the report for consistency.	KHA 12/5/2006
8	Table 2.6	Middle column5th entry from bottom of table. ηT01, should be η1100 or 1150(Typo)	E		This refers to the viscosity at the temperature T01.These values were calculated for the algorithm glasses, although they were not used as constraints. The glass in question has the minimum calculated viscosity at T01 (also at 1100°C and 1150°C). In order	KHA 12/5/2006

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
					to maintain traceability of the algorithm formulation ID, the label of ηT01 (as provided by the WTP Project) should be kept.	
9	Table 4.7	Footnote c. "large extrapolation". This term needs to be explained and clarified/better defined in the text. It is not a very scientific term.	I		We will add a more quantitative qualifier to the footnote (e.g., > 100°C beyond the experimental temperature limits).	KHA 12/5/2006
10	Table 4.8	Footnote to be complete should also note that the leachate pH is rounded to 2 decimal places. Presently, it only mentions the other 2 categories of data in the table.	I		The leachate pH was measured to 2 decimal places. However, the reported pH value is an average of three triplicates and rounded to 2 decimal places during averaging. Suggested addition will be made.	KHA 12/5/2006
11	Overall	Good Report.			Thank you.	—

[a] **Significance**: M = Mandatory; I = Improvement. Definitions for these terms are provided at the end of the form instructions and in Appendix B of procedure "WTP Document Administration".

[b] Justification required for Mandatory Comments.