DISCLAIMER

HFO-72295
Revision 0

PREPARATION AND TESTING OF HLW MATRIX GLASSES TO SUPPORT DEVELOPMENT OF WTP PHASE 2 PROPERTY-COMPOSITION MODELS, VSL-06R6780-2, REV. 0

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

P.O. Box 550
Richland, Washington 99352

HFO-72295
Revision 0

PREPARATION AND TESTING OF HLW MATRIX GLASSES TO SUPPORT DEVELOPMENT OF WTP PHASE 2 PROPERTY-COMPOSITION MODELS, VSL-06R6780-2, REV. 0

W. K. Kot
Vitreous State Laboratory of The Catholic University of America

H. Gan
Vitreous State Laboratory of The Catholic University of America

I. L. Pegg
Vitreous State Laboratory of The Catholic University of America

Date Published
November 2006

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

P.O. Box 550
Richland, Washington 99352

APPROVED
By Lynn M Ayers at 4:35 pm, Aug 20, 2025

Release Approval Date

VSL-06R6780-2

Final Report

Preparation and Testing of HLW Matrix Glasses to Support Development of WTP Phase 2 Property-Composition Models

prepared by

Wing K. Kot, Hao Gan, and Ian L. Pegg

Vitreous State Laboratory
The Catholic University of America
Washington, DC 20064

for

Duratek, Inc.

and

Bechtel National, Inc.

September 26, 2006

Rev. 0, 11/7/06

Document Title: Preparation and Testing of HLW Matrix Glasses to Support Development of WTP Phase 2 Property-Composition Models

Document Number and Revision: VSL-06R6780-2, Rev. 0
Issue Date: November 7, 2006
Performing Organization: Vitreous State Laboratory, The Catholic University of America
Test Specifications: 24590-HLW-TSP-RT-01-006, Rev. 1
Test Exceptions: 24590-WTP-TEF-RT-03-078, Rev. 0
Test Plans: VSL-02T7800-1, Rev. 1
R&T Focus Area(s): HLW Waste Form Qualification
Test Scoping Statement(s): VSL-13, VSL-14

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:** 11/7/06
VSL Program Director/Principal Investigator

I. Joseph: Innocent Joseph **Date:** 11/7/06
Duratek Sub-Contract Manager

TABLES OF CONTENTS

List of Tables

List of Figures

List of Abbreviations

AES	Atomic Emission Spectroscopy
ANL	Argonne National Laboratory
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
ILAW	Immobilized Low Activity 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
PNWD	Battelle—Pacific Northwest Division
QARD	Quality Assurance Requirements and Descriptions Document
QGCR	Qualified Glass Composition Region
RPP	River Protection Project
RSD	Relative Standard Deviation
SD	Standard Deviation
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 is one in a series of reports that presents the results from the High Level Waste (HLW) glass formulation development and testing work performed at the Vitreous State Laboratory (VSL) of the Catholic University of America (CUA) to support the development of Immobilized High Level Waste (IHLW) property-composition models for the River Protection Project-Hanford Tank Waste Treatment and Immobilization Plant (RPP-WTP). Specifically, this report presents results of Phase 2 glass testing at VSL to support the development of IHLW Product Consistency Test (PCT), melt viscosity, electrical conductivity, and one-percent crystal fraction temperature ($T_{1\%}$) models. The data will be used to augment and refine models developed in Phase 1 testing. The Phase 2 IHLW PCT model will be used to support qualification of the IHLW products, whereas the Phase 2 IHLW viscosity, electrical conductivity, and $T_{1\%}$ models will support operation of the WTP. Completion of the test objectives is addressed in the table below.

Test Objective	Objective Met	Discussion
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 glasses from a statistically designed Phase 2 matrix 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	In addition to the 40 IHLW Phase 2 matrix glasses, viscosity and electrical conductivity data were collected on 10 glasses selected from IHLW Phase 1 test matrices. The data are given in Section 4. The Phase 1 glasses were selected to provide coverage of data gaps in both the compositional space and property values. The collected data will be used together with data from 102 other Phase 1 glasses to support development of the respective models.
Develop models for liquids 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, will support further development of the $T_{1\%}$-property model for spinel (as the principal phase) that was previously developed and reported. Data have been collected and $T_{1\%}$ values were estimated for Phase 2 matrix 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 that is being used to support a petition to delist IHLW glasses. 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 test exception was effective during Phase 1 testing. The current tests followed the same directive and determined $T_{1\%}$ instead of T_L.

C) Results and Performance Against Success Criteria

The data in this work are based on a 2-layered statistically-designed matrix of glasses that comprised 40 Phase 2 HLW glasses, including 4 replicates of Phase 1 glasses previously tested. Additionally, 10 glasses were selected from Phase 1 HLW matrices ("Non-Spinel Matrix" and "Spinel Matrix") to be characterized with respect to melt viscosity and electrical conductivity (other testing was completed during Phase 1).

The normalized PCT releases measured for the HLW Phase 2 matrix glasses varied from 0.192 g/l to 6.065 g/l for boron, 0.071 g/l to 4.768 g/l for sodium, and 0.321 g/l to 4.561 g/l for lithium. These can be compared with the PCT release values for the DWPF-EA glass: 16.695 g/l for boron, 9.565 g/l for lithium, and 13.346 g/l for sodium. Thus, all the matrix glasses outperformed the DWPF-EA glass, an observation that was also noted during Phase 1 testing. Similar to the PCT data collected in Phase 1, the Phase 2 matrix glasses have normalized PCT releases that are distributed mostly around the low-release region. While it is desirable for the purpose of model development to include HLW glasses that exceed the reference glass in terms of PCT releases, it appears that the use of other property constraints (e.g., viscosity) results in glasses with limited and generally low PCT releases. The relative pooled standard deviations of the PCT releases for the four replicate pairs range from 12% to 14%, which is comparable to or better than those from Phase 1 testing.

Viscosity and electrical conductivity were measured for 50 HLW glasses, including 10 selected from Phase 1 matrices and all 40 Phase 2 matrix glasses. Fitting to the Vogel-Fulcher equation gave interpolated values of viscosity and electrical conductivity at standard temperatures (e.g., 1150°C). The Phase 1 glasses are relatively evenly distributed in terms of their (fitted) electrical conductivity values at 1150°C, with all data falling within the design range of 0.2 S/cm to 0.7 S/cm. The viscosity values of the Phase 1 glasses at 1150°C, on the other hand, show more scatter and only five are within the design range of 10 P to 100 P. For the Phase 2 glasses, a fair number fall outside the design ranges: 14 for viscosity and 13 for conductivity. Additionally, two Phase 2 glasses were found to have viscosities considerably above the design upper limit of 100 P at 1150°C (> 250 P), suggesting that model improvements may be required for viscosity predictions at the high end. The pooled relative standard deviations for the replicates are 13.6% and 10.1% for the viscosity and electrical conductivity measurements, respectively.

Of the 40 HLW Phase 2 matrix glasses, $T_{1\%}$ values could be estimated for 39, spinel being the dominant crystalline phase. With the exclusion of replicates and glasses that crystallized non-spinel phases, the estimated $T_{1\%}$ data span a range of 750.0°C to 1059.3°C. The median $T_{1\%}$ is 955.3°C, which can be compared with the WTP processing requirement of $T_{1\%} \leq 950$°C. When all Phase 2 matrix glasses are included, the estimated $T_{1\%}$ data range from 750.0°C to 1316.7°C, with a median of 978.1°C. This can be compared with the range of 554.2°C to 1481.4°C and a median of 958.2°C found for the Phase 1 $T_{1\%}$-modeling study. The pooled relative standard deviation of the estimated $T_{1\%}$ values for the replicate pairs is 29.94°C.

The PCT, viscosity, electrical conductivity, and $T_{1\%}$ data will be used in subsequent work to augment and refine previously developed Phase 1 property-composition models.

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.

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 compositions of the HLW Phase 2 glasses were developed at Battelle—Pacific Northwest Division (PNWD) by applying statistical experimental design methods to optimally cover compositional regions. The compositional ranges were defined by various constraints, using the previously designed matrices as the augmentation basis. The WTP Project provided the bases for the compositional ranges while the constraints were developed at VSL by considering a variety of inputs, including waste compositions and glass properties.

The 40 Phase 2 matrix 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 $T_{1\%}$. The 10 glasses selected from Phase 1 matrices were characterized with respect to melt viscosity and electrical conductivity only (all other properties were measured previously during Phase 1 testing). All of these data are reported herein.

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 Phase 2 matrix glasses and the leachates were analyzed by Direct Current Plasma-Atomic Emission Spectroscopy. The melt viscosities of the matrix glasses were measured, typically in the temperature range of 950-1250ºC, using a rotating spindle viscometer, with the viscosity determined from the relation between torque and rotation speed. Electrical conductivity was determined by measuring the resistance 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 Phase 2 matrix glasses were heat treated isothermally between 700°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 to identify the crystalline phases and to estimate their volume fractions.

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 wastes, are generally more suited for melter tests than crucible scale preparation of glasses (since glass properties are in general not dependent on physical and rheological properties of the starting materials). All of the simulated glasses in this work were instead prepared from reagent grade chemicals in combinations designed to achieve the target compositions in the statistically-designed test matrices.

G) Discrepancies and Follow-On Tests

There were no discrepancies. The work reported herein completed data collection for the planned testing of HLW glasses designed to support development of property-composition models. The Phase 2 model development effort will follow, with the new data being used to refine and improve the final WTP models for the IHLW PCT, $T_{1\%}$, viscosity, and electrical conductivity. While there are currently no follow-on tests planned, all glass samples that remain from the present testing have been archived and will be available for future testing at VSL, if so directed by the Project (e.g., TCLP). It should be noted, however, that the amounts of samples archived vary and may be sufficient only for a limited number of tests.

SECTION 1
INTRODUCTION

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

This report is one in a series of reports that present the results from High Level Waste (HLW) glass formulation development and testing work performed at the Vitreous State Laboratory (VSL) of the Catholic University of America (CUA). Specifically, this report presents results of WTP glass testing conducted between December 2005 and September 2006. The work included support of the statistical design of the WTP HLW Phase 2 test matrix, fabrication of the matrix glasses, and characterization of the resulting glasses. The characterization included Product Consistency Test (PCT) response, measurements of melt viscosity and electrical conductivity, and determination of $T_{1\%}$, which is the temperature at which the volume fraction of crystals in equilibrium with glass melt equals 1%. This work continues the Phase 1 testing efforts to develop IHLW property-composition models. During Phase 1 testing, four HLW test matrices were statistically designed to generate 167 matrix glasses, which were then fabricated and characterized at VSL. Two previous reports [1, 2] described the results from Phase 1 testing and the development of IHLW property-composition models that relate PCT responses (i.e., releases of boron, lithium, and sodium) and $T_{1\%}$ to glass composition. In addition to augmenting and refining those earlier models, the Phase 2 testing data presented in the present report will also be used to support the development of models that predict melt viscosity and electrical conductivity based on glass compositions.

This report is responsive to the Test Specification [3], Test Plan [4], and Test Exception [5] for HLW property-composition modeling. The objective of the work described in these documents is to develop property-composition models to support HLW waste form qualification and processing. It is intended that the models will provide the basis to define the Qualified Glass Composition Regions (QGCRs), operating ranges, and target glass compositions for HLW processing at the WTP. As proposed in the Test Plan [4], a staged approach is adopted to allow continual incorporation of evolving information and data on waste compositions and process knowledge, whereby updates and improvements to the property-composition models will help define the most appropriate QGCRs. The primary objective of this work is, therefore, to integrate the current understanding and projections of the tank waste and glass compositions. Further, since this is the final testing phase planned to support model development, another objective of the present work is to fill in any composition and property data gaps that remained from earlier testing such that the composite data set used in developing the final property-composition models will have an adequate region of validity. Development of the final HLW property-composition models will be performed and reported at a later date.

1.1 Test Objectives

The objectives of the HLW glass property-composition modeling work as given in the Test Plan [4] are listed below along with the strategy to address them.

- *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 [1]. Data collected from 102 HLW glasses (including replicates) from two statistically designed matrices were used as the basis for model development. Additional PCT data have also been reported for 35 HLW glasses from the Phase 1 Spinel Matrix [2].

  The PCT data presented in this report were collected from 40 Phase 2 matrix glasses, which were designed to incorporate updated projections of tank waste and HLW glass compositions. The collected PCT data will be used to refine and update the Phase 1 PCT models at a later time.

- *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 [5], instead of liquidus temperature (T_L) models, models to predict one-percent crystal fraction temperatures ($T_{1\%}$) have been developed. These have been reported previously [1, 2]. 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 data presented in this report are collected primarily to estimate $T_{1\%}$, which will be used to develop and refine models to predict $T_{1\%}$ instead of T_L.

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) (including the Spienl Matrix for waste group (i) and the Non-Spinel Matrix for waste group (ii)), each focusing on the expected characteristic compositions of the two groups [1, 2]. Preliminary $T_{1\%}$ models suitable for predicting spinel as the primary crystalline phase have been developed and reported [1]. 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 present tests made use of the latest projections of waste compositions and the data generated will be used to augment Phase 1 data for both spinel and non-spinel phases.

- *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 [6]. The Phase 2 HLW matrix glasses were not characterized with respect to TCLP responses. However, samples of the matrix glasses that remain after current testing have been archived and will be available for future testing at VSL, if so directed by the Project. The future testing may include TCLP if the quantities of the archived samples are sufficient.

- *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 [7].

The current testing provides viscosity and electrical conductivity data for 40 Phase 2 matrix glasses and 10 Phase 1 matrix glasses. The Phase 1 matrix glasses were selected from the Non-Spinel Matrix (designated as HLW05) and the Spinel Matrix (HLW06) [2]; glasses from the Non-Spinel Matrix and the Spinel Matrix have not been characterized previously with respect to viscosity and electrical conductivity. These glasses were selected to provide coverage of expanded glass compositional ranges (of the Non-Spinel Matrix and Spinel Matrix from Phase 1) and good distribution of predicted viscosity and electrical conductivity values. The combined data from the 10 Phase 1 and 40 Phase 2 glasses will be used to develop IHLW 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 development of property-composition models has been a process jointly undertaken by VSL and Battelle-Pacific Northwest Division (PNWD) during Phase 1 of the IHLW modeling efforts [1]. The process consists of:

(i) The development of constraints on IHLW components describing the IHLW EGCRs of interest.

(ii) Statistical design of the test matrix.

(iii) Fabrication of the test glasses in the test matrix.

(iv) Characterization of the fabricated glasses, including PCT, viscosity, electrical conductivity and $T_{1\%}$.

(v) Investigation and selection of initial mathematical model forms.

(vi) Detailed statistical analyses of the collected data to develop and refine the corresponding models.

The current tests follow a similar process and the data will supplement results obtained from Phase 1. However, this report summarizes the results of only steps (i), (iii) and (iv) performed at VSL. Detailed description of the statistical design of the test matrix, which was performed at PNWD, will be reported at a later time together with analyses and modeling of the data (PNWD will make use of the collected data to augment and refine previous IHLW models).

Development of the design constraints for the Phase 2 test matrix, which is discussed in Section 2, required a variety of considerations and inputs including waste compositions. The development approach followed closely those employed in Phase 1, with updated tank waste compositions and flow-sheet projections of glass composition ranges being substituted for those used in Phase 1. Statistical experimental design based on the developed constraints, which was performed at PNWD, resulted in the Phase 2 test matrix of 40 HLW glasses. Section 2 briefly describes the statistical design (as stated above, the statistical design of the Phase 2 test matrix will be reported in detail together with the results of the modeling work once that is completed).

After generation of the test matrix, the 40 test glasses were fabricated (on ≈ 420 g scale) using reagent-grade chemicals in platinum alloy crucibles and then were tested at VSL. Among the tests performed were PCT, viscosity and electrical conductivity measurements, and crystal fraction determinations as a function of heat-treatment temperature. The collected heat-treatment data were then analyzed by linear regression to estimate the one-percent crystal fraction temperatures ($T_{1\%}$). Fabrication and testing of the matrix glasses are described in Section 3. Section 4 presents and summarizes the test data.

In addition to the 40 Phase 2 matrix glasses, 10 glasses were selected by PNWD from two Phase 1 matrices (five from the Non-Spinel Matrix and five from the Spinel Matrix) for the collection of viscosity and electrical conductivity data. These glasses were selected to provide coverage of expanded glass compositional ranges (for the Non-Spinel Matrix and Spinel Matrix from Phase 1) and good distribution of predicted viscosity and electrical conductivity values to augment existing data. Since archive samples of these glasses were used in the viscosity and electrical conductivity measurements, fabrication of these glasses, which has been reported previously [2], was not performed in the present work. The process leading to their selection is discussed in Section 2, and the collected data are presented in Section 4.

SECTION 2
DEVELOPMENT OF TEST MATRIX

In order to develop property-composition models, adequate property-composition data covering the experimental glass composition regions (EGCRs) of interest are required. This section describes the development and generation of the Phase 2 test matrix of 40 HLW glasses to support the collection of the necessary data for four relevant HLW glass properties: PCT releases, viscosity, electrical conductivity, and $T_{1\%}$. The design and development of the Phase 2 test matrix followed closely the approaches employed in Phase 1 testing, including the adoption of a 2-layered design (see below); it also drew heavily from the experience and results of Phase 1 testing [1, 2]. Section 2.1 summarizes the constraints used in designing the WTP HLW Phase 2 matrix, while Section 2.2 briefly describes the development of the matrix, which was performed at PNWD. Section 2.4 presents the compositions of the matrix glasses generated.

2.1 Matrix Design Constraints

The primary objective of the Phase 2 matrix design was to augment the existing glass property-composition data collected during Phase 1 to reflect the current understanding of tank waste compositions to be processed at the WTP vitrification facility. As a secondary objective, the matrix design was intended to fill in composition and property regions that have limited coverage by the data collected during Phase 1. The following starting points were used in formulating constraints to design the HLW Phase 2 matrix:

- Statistically-designed HLW glass test matrices from Phase 1 (HLW02, HLW03, HLW05 and HLW06) that provide the existing data.
- Property constraints employed in previous matrix designs and the glass property-composition models developed during Phase 1.
- Current understanding of the tank waste compositions and flow-sheet projections of major glass components.
- Contract waste loading requirements.

The data from the Phase 1 studies were analyzed and evaluated using:

- Histograms of the distribution of major glass components and key properties.
- Selected pair-wise scatter plots of component vs. component or property vs. components.

Table 2.1 summarizes some of the observations and conclusions based on the evaluation of Phase 1 data, which provided guidelines for selecting the appropriate constraints to design the Phase 2 test matrix.

2.1.1 HLW Glass Composition Constraints

The WTP Project provided the primary input for the current tank waste compositions and projected HLW glass compositional ranges [8]. Table 2.2 lists the 17 HLW glass components used to define the EGCR for the HLW Phase 2 matrix design and their respective lower and upper limits in the outer and inner layers. Also listed for comparison in Table 2.2 are the concentration ranges of the same components for the glasses from the Phase 1 test matrices. The division of glass constituents in the Phase 2 matrix design is summarized as follows:

- Major glass oxides or oxides that are known to significantly affect glass properties were treated as design variables. A total of 14 single components are listed in Table 2.2 (i.e., Al_2O_3, B_2O_3, …, ZrO_2).
- Minor constituents were treated either as components of a grouped variable, denoted as “Others,” or design constants, denoted as “Constant.”
- Two grouped variables were employed: “Others1” and “Others2”. Tables 2.3 and 2.4, respectively, list the mixture of minor oxides that made up “Others1” and “Others2.” Tables 2.3 and 2.4 also provide the maximum concentrations of the individual components that can be found in the Phase 2 matrix glasses and the bases for selecting these concentrations. In many cases, the maximum required value of a minor oxide has been achieved in a Phase 1 matrix, and the Phase 2 matrix explores smaller but more realistic values. In other cases, the maximum required value is achieved in the current design and corresponds to the WTP contract requirement or the WTP flow-sheet projection.
- Table 2.5 lists the compositional makeup of the group “Constant.” Note that “Constant” is actually a variable component in the Phase 2 matrix design since it is constant only separately for the outer layer and the inner layer (see Section 2.2). Further, Ta_2O_5 was inadvertently left out of the compositions in the design of the Phase 2 matrix glasses and was not included in the actual melting of the glasses. Table 2.5 lists both the original design composition of “Constant” and its composition in actual glasses melted.
- Table 2.6 lists the components that have been studied in Phase 1 test matrices and were excluded from the Phase 2 matrix design. However, since the Phase 2 test matrix included four replicates of Phase 1 glasses, some of the components in Table 2.6 are found in the Phase 2 HLW glasses and they were grouped for convenience into a group denoted as “Remaining,” bringing the total number of components in the Phase 2 matrix design to 18. The oxides that made up “Remaining” and their concentrations vary, depending on the actual compositions of the Phase 1 test glass being replicated.

2.1.2 Waste Loading Constraint

Similar to the design of Phase 1 matrices, the waste loading constraint was developed based on the requirements of Contract Specification 1.2.2.1.6, "Product Loading" [9]. The relevant requirement in the specification is $Al_2O_3 + Fe_2O_3 + ZrO_2 \geq 21.0$ wt%. The constraint of

$$Al_2O_3 + Fe_2O_3 + ZrO_2 \geq 18.0 \text{ wt\%}$$

was used to help define the EGCR for the HLW Phase 2 study. This can be compared with the concentration ranges of the single components in Table 2.2, which suggest that the minimum value of $Al_2O_3 + Fe_2O_3 + ZrO_2$ can reach 8.0 wt% for the outer layer and 13.5 wt% for the inner layer without the use of any waste loading constraints.

In contrast to the design of the Phase 1 Non-Spinel Matrix, no upper-limit constraint was used for the current design. Instead, waste loading was indirectly limited by other constraints such as the glass property constraints (Section 2.1.3).

2.1.3 Glass Property Constraints

As discussed in Section 2.1, evaluation of data from Phase 1 studies provided the bases for selecting constraints for the Phase 2 matrix design. Based on the property distribution of existing matrix glasses (Table 2.1), the following glass property constraints were considered in the Phase 2 matrix design:

- Existing data for viscosity at 1150°C are heavily skewed to the lower end, with the majority of the data found between 10 P and 40 P. While additional data in the range of 50 to 80 P would be desirable, such constraints were deemed too tight for the Phase 2 matrix design. The lower and upper limits for viscosity at 1150°C were, therefore, maintained at the same levels as those in Phase 1, i.e., 10 P and 100 P (the WTP processing limits).
- Existing data for electrical conductivity at 1150°C are more evenly distributed than those for viscosity. Although Table 2.1 suggested that additional data around 0.4 to 0.5 S/cm would be desirable, imposing such tight constraints would severely limit the EGCR available for study. The lower and upper limits for electrical conductivity at 1150°C were therefore maintained at the same levels as those in Phase 1, i.e., 0.2 S/cm and 0.7 S/cm (the WTP processing limits).
- In spite of the fact that PCT constraints were not used in designing the Phase 1 Spinel Matrix, all glasses from that matrix significantly outperformed the reference DWPF-EA glass [2]. It was apparent that implementation of other property constraints (e.g., viscosity) indirectly limited PCT releases such that no PCT constraints were necessary to ensure the test glasses would meet the PCT performance requirements. Although it is desirable for the purpose of model development to include HLW glasses that exceed the reference glass in terms of

PCT releases, it would be artificial to specify an unrealistic EGCR sub-region with high PCT releases in order to fill the data gaps. It was therefore decided that no constraints would be used on PCT releases.

- The spinel $T_{1\%}$ data from Phase 1 studies were relatively evenly distributed [1, 2]. The present study is therefore centered on glasses with spinel $T_{1\%}$ values around the WTP processing requirement of ≤ 950°C. The upper limit of 1000°C was employed for the spinel $T_{1\%}$.
- As seen in Table 2.2, the upper limits for ThO_2 and ZrO_2 concentrations have been reduced when compared to the upper limits used in the Phase 1 Non-Spinel Matrix [2]. This was expected to decrease the number of glasses that would be limited by crystallization of Th- and Zr-containing phases. In addition, since no reliable models were available to implement the constraint, no constraints were used on $T_{1\%}$ for Th- and Zr-containing phases.
- The constraints used in the design of some of the Phase 1 matrix glasses included TCLP responses [6]. Test data collected on those glasses have already been used in developing TCLP models to support a delisting petition. The current design of the Phase 2 HLW matrix therefore did not include TCLP response as a property constraint.

The same property constraints were used for both the outer and inner layers. This was because the concentration limits for both layers were chosen to fill in the existing data gaps and there were no obvious advantages to employing different constraints for the two layers.

Table 2.7 summarizes the glass property constraints for the HLW Phase 2 matrix and the property-composition models used to implement them.

2.2 Development of HLW Phase 2 Test Matrix

A 40-glass HLW Phase 2 layered design was constructed at PNWD based on the glass component and property limits discussed above. The HLW glasses from both outer and inner layers were selected to optimally augment 125 existing HLW glasses with data for all properties of interest (PCT, viscosity, electrical conductivity, and $T_{1\%}$) [1]. The approach of augmenting only glasses that have data available for every property was chosen to provide an optimized common set of data to develop models for those four properties. The matrix included 14 single component variables, 2 grouped multi-component variables, and 1 grouped multi-component constant. Minor oxides that were not included in the Phase 2 design but that were present in the replicate glasses were grouped as "Remaining."

Generation of the HLW Phase 2 test matrix involved a multi-step process and followed similar approaches to those employed in Phase 1. The detailed steps of the process used to generate the Phase 2 matrix will be described in a subsequent report.

The resulting HLW Phase 2 test matrix contains:

- the center point glass of the inner layer (designated as HLW07-01);
- replicates of four glasses studied in Phase 1 (HLW07-02 through -04, respectively replicating HLW02-46, HLW03-41, HLW02-22, and HLW03-07);
- 20 outer-layer glasses (HLW07-06 through -25);
- 15 inner-layer glasses (HLW07-26 through -40).

Table 2.8 lists the 18-component compositions of the HLW Phase 2 matrix glasses. Table 2.9 gives the expansions of "Others1," "Others2," and "Constant," while Table 2.10 gives the expansions of the "Remaining" component.

2.3 Selection of Phase 1 Glasses for Viscosity and Electrical Conductivity Measurements

During the Phase 1 studies, the Non-Spinel Matrix (HLW05) and Spinel Matrix (HLW06) were designed to have expanded compositional ranges compared to earlier matrices [2]. Glasses from the Non-Spinel Matrix and Spinel Matrix, however, were not characterized with respect to viscosity and electrical conductivity. In order to develop property-composition models for viscosity and electrical conductivity with similar valid compositional regions as the other models, it was decided to measure the viscosity and electrical conductivity of a subset of the HLW05 and HLW06 glasses. The goal was to select a subset to expand the component ranges covered for viscosity and electrical conductivity such that they would be similar to the component ranges covered for PCT and spinel $T_{1\%}$.

Although there were 65 glasses available from the two matrices, experience at VSL suggested that glasses with high $T_{1\%}$ values may show crystallization during measurement, thereby compromising the viscosity and electrical conductivity measurements themselves. It was, therefore, decided to limit the selection to glasses with $T_{1\%} > 950$ºC, which left only 25 suitable glasses. Subsets of 5, 10, and 15 glasses were selected from these 25 candidates using optimal experimental design software to augment 143 Phase 1 glasses with data for viscosity and electrical conductivity. The subsets of 5, 10, and 15 glasses were compared graphically to the set of 143 HLW Phase 1 glasses. The goal was to cover the expanded component ranges with as few glasses as possible, and also to obtain a good distribution of predicted viscosity and conductivity values. It was decided that the subset of 10 glasses provided better coverage of the component ranges than the subset of 5 glasses, whereas the subset of 15 glasses did not significantly improve the coverage. A total of 10 glasses (5 HLW05 glasses and 5 HLW06 glasses), therefore, were selected at PNWD using D-optimal design software (more details of the selection process will be provided in a later report). Viscosity and electrical conductivity were then measured on archived samples of these glasses at VSL; the data are presented in Section 4 (PCT and $T_{1\%}$ data for these glasses have been reported previously [2]). Table 2.11 lists the selected glasses and their compositions.

SECTION 3
EXPERIMENTAL PROCEDURES

After completion of the statistical design of the Phase 2 HLW matrix at PNWD, the matrix 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 Phase 2 matrix glasses are summarized in this section.

3.1 Glass Batching and Preparation

All HLW Phase 2 matrix glasses were fabricated at VSL using reagent grade chemicals and solutions of known purity. Glasses selected from the Phase 1 matrices were not fabricated for these tests; instead, archived samples of the selected glasses were used in viscosity and electrical conductivity measurements. The Technical Procedure *Crucible Melts* [10] describes the details of crucible preparation of HLW glasses. The following section summarizes the procedural steps.

3.1.1 Batching of Starting Materials

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.

Calculation of the required amounts of starting materials in the batching sheets made use of not only purity information, but also volatility characteristics of the chemicals. Specifically, thallium (III) oxide, which was used as the starting material for thallium (I) oxide in glass, is relatively volatile, with a boiling point of only 875 °C, and substantial loss is expected at the glass-melting temperature of over 1000°C. Previous glass formulation work at VSL has accumulated a data base of thallium-containing glasses [11, 12], which suggested that thallium loss may vary with concentration and glass composition. On average, however, those data showed that only 54 wt% of the starting thallium (III) oxide was retained in glass. Consequently, thallium (III) oxide was "over-batched" by a factor of 1.85 in the batching sheets for the preparation of glasses. Another volatile component, selenium (IV) oxide, was "over-batched" by a factor of 2.29.

In batching recipes for preparing these HLW glasses, over 40 components might be needed. It was possible to take advantage of the fact that many of those components were present in the HLW glasses in constant concentrations. Glass frits, which consisted of 13 components, were therefore employed as a starting material in the batching of the HLW matrix glasses in order to reduce the number of components required.

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. A pre-weighed noble metals solution (a nitric acid solution of ruthenium (Ru), rhodium (Rh), and, in the case of replicate glasses, palladium (Pd)), which also contained cesium (Cs) and rubidium (Rb), was then added and blended with the chemicals. Addition of the noble metals as a solution instead of as a solid (typically less than 0.5 g of oxide was required) was found to aid in the dispersion of noble metals in the glasses.

3.1.2 Glass Melting

Glass melting was performed in a random order with the exact sequence of melts determined by assigning a random number to each HLW glass and then placing the glasses in ascending order according to the associated random number. The melt order is listed in Table 2.8. After the melt order had been determined and the batching completed, 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 Analysis of Glass Composition

Compositions of the HLW glasses were analyzed with 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 a glass melt, η, was measured using a Brookfield viscometer, with the viscosity determined from the relation between torque and rotation speed. Measurements were normally performed in the temperature range of 950ºC to 1250ºC and, to facilitate comparison, the data were interpolated to standard temperatures (e.g., 1150ºC) 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 at 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 by measuring the impedence 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); individual measurements, however, were made at comparable but not identical temperatures. The results were extrapolated to zero frequency to obtain the direct current conductivity. To facilitate comparison, the measured data were then interpolated to standard temperatures (e.g., 1150ºC) 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 Phase 2 HLW matrix glasses were collected at VSL from tests performed at 90°C for 7 days according to ASTM C1285 [13], as required in Specification 1 of the WTP contract [9]. Samples of crushed glasses (4 g, −100 mesh and +200 mesh, or 75 µm to 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 DWPA-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:

$$r_i = \frac{c_i}{f_i} \ , \qquad (3.5.1)$$

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:

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

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 g/l, 13.346 g/l, and 9.565 g/l for B, Na, and Li, respectively [14]. 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 700°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, a sufficient number of heat treatments were performed to obtain non-zero vol% data for at least three temperatures in order to reasonably constrain the $T_{1\%}$ value. Effort was 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 were 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 [1], 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.

SECTION 4
RESULTS AND DISCUSSION

This section presents the characterization and test data for the matrix glasses. Chemical compositions of the matrix glasses, determined by XRF analyses, are presented in Section 4.1. The Product Consistency Test (PCT) was performed on all Phase 2 HLW matrix glasses (40 glasses) and the data are discussed in Section 4.2. In addition to the melt viscosity and electrical conductivity data for all Phase 2 matrix glasses, Section 4.3 also presents viscosity and electrical conductivity data for 10 Phase 1 HLW matrix glasses (5 each from the Non-Spinel Matrix and the Spinel Matrix). Section 4.4 summarizes the heat-treatment data for the 40 Phase 2 HLW 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.

4.1 Chemical Composition

Results of compositional analysis by XRF of the Phase 2 matrix glasses are given in Table 4.1. Note, however, that the batched (target) compositions are used below for calculating normalized PCT responses (and for future modeling efforts) since they are derived from simple weighing of pure chemicals, which are believed to provide the best compositional data; previous modeling work followed the same approach [1]. 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. However, for selected minor components, especially barium and magnesium, some discrepancies are evident. For example, analysis of HLW07-03 showed no presence of BaO, even though the target value was 0.13 wt%. 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.

4.2 Product Consistency Test (PCT) Results

The data for PCT releases of boron, lithium, sodium, and silicon for the 40 Phase 2 matrix 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 normalized PCT boron, lithium, and sodium releases for all 40 Phase 2 matrix glasses. As expected from the matrix design, glasses from the outer layer of the design (HLW07-06 through -25) show considerably more scattered and extreme PCT releases, a reflection of the expanded composition ranges explored in the outer layer. However, all of the measured PCT responses are well below the nominal values for the reference DWPF-EA glass (not shown in the figures); the normalized boron PCT releases range from 0.192 g/l to 6.065 g/l (both are for outer-layer glasses), compared with 16.695 g/l for DWPF-EA. For lithium and sodium, the ranges of measured normalized PCT releases are, respectively, 0.321 g/l to 4.561 g/l and 0.071 g/l to 4.768 g/l, compared with the corresponding nominal values of 13.346 g/l and 9.565 g/l for the DWPF-EA glass. As discussed in Section 2, no PCT constraints were imposed in the design of the Phase 2 test matrix. As noted earlier, there is a general paucity of data for high PCT releases (e.g., PCT B releases > 5 g/l) among the Phase 1 test glasses and the current data again are distributed mostly around the low-release region. For example, only 5 glasses are found to show normalized PCT B releases above 2 g/l (Figure 4.1). This confirms the observation made in Phase 1 testing, that glasses found in the EGCR are unlikely to exhibit PCT responses that approach or exceed the DWPF-EA glass limits. While it may be desirable for the purpose of model development to include IHLW glasses that span a wider range of PCT performance, it appears that the use of other property constraints results in glasses with limited, and generally low PCT releases.

The Phase 2 test matrix design includes replicates of four glasses studied previously in Phase 1. Table 4.3 identifies these replicate pairs and gives the associated PCT data. The relative standard deviations (RSD) in Table 4.3 suggest that the agreement between the replicates is generally comparable to (or, in the case of boron, better than) those from Phase 1 tests [1, 2], in spite of the longer time period that covers the testing of the current replicate pairs (fabrication and PCT testing of the Phase 1 HLW02- and HLW03- glasses commenced in December 2002 and concluded in August 2003.) Table 4.4 compares the pooled relative standard deviations obtained from the different phases of testing.

Another measure of the uncertainty associated with PCT testing can be obtained from comparing the results of the reference glass that was included in each test set (DWPF-EA). Table 4.5 gives the PCT results for the DWPF-EA glass from nine sets of testing. The %RSDs in Table 4.5 are better than those reported previously [14]. They are also generally smaller than those found for the replicate pairs, which is not unexpected since glass fabrication as a source of variation is not present here (samples from a bulk source of DWPF-EA glass were used). The average measured PCT release of boron, however, is somewhat higher than the nominal value.

4.3 Viscosity and Electrical Conductivity Results

Table 4.6 lists the measured and fitted viscosity results for the 10 selected Phase 1 glasses, and Table 4.7 lists the measured and fitted electrical conductivity results for the same glasses. Figures 4.4 and 4.5 respectively display the distribution of the fitted viscosity and electrical conductivity of all 50 glasses (10 Phase 1 and 40 Phase 2 glasses) at 1150°C. Figure 4.5 shows that the (fitted) electrical conductivity data at 1150°C all fall within the range of 0.2 S/cm to 0.7 S/cm with a relatively even distribution. In contrast, Figure 4.4 shows that the viscosity results of seven glasses are found within the design range of 10 P to 100 P (the measured viscosity data for one glass were not fitted to the Vogel-Fulcher equation because of non-newtonian behavior). Figure 4.4 also shows that two glasses have viscosity values considerably above the design upper limit of 100 P, suggesting that the viscosity model used in designing the matrix constraints may need improvement towards the high range.

Table 4.8 lists the measured and fitted viscosity results for all 40 HLW Phase 2 matrix glasses, and Table 4.9 lists the measured and fitted electrical conductivity results for the same glasses. Figures 4.4 and 4.5, respectively, display the distribution of the fitted viscosity and electrical conductivity of these glasses at 1150°C. It is seen in the figures that a fair number of glasses fall outside of the design ranges: 14 for viscosity (excluding replicates) and 13 for electrical conductivity. Two outer-layer glasses are found to have viscosities of over 250 P at 1150°C. This reinforces the observation that improvement may be needed in the performance of the viscosity models at the high-viscosity end.

Table 4.10 presents the pairwise and pooled standard deviations for the viscosity and electrical conductivity results for the four replicate pairs. The pooled standard deviations are in the expected range of 10% to 15%.

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

Heat treatment of the matrix glasses was conducted between 700°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 at least 50°C apart. Table 4.11 lists the measured crystal vol% data for the Phase 2 matrix glasses. Fitting of these data to a regression equation of the form

$$T = a_0 + a_1 X, \tag{4.1}$$

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

provided estimates of $T_{1\%}$ for the matrix glasses. Table 4.12 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 $T_{1\%}$. Figure 4.6 shows the distribution of the estimated $T_{1\%}$ values. Appendix A presents plots of the experimental data and the calculated regression results for all 40 glasses.

As can be seen in the plots of vol% crystals against heat treatment temperature (Appendix A), the typical correlation observed between crystal vol% and heat treatment temperature is relatively simple and can be adequately described by a linear relationship (Equation 4.1). In a few cases, the temperature dependence is non-linear. For example, the data for the glass HLW07-03 show a change of sign of the slope. This change has been observed previously in the measurements of the Phase 1 glasses [2] and is presumably due to the increases in melt viscosity at lower temperatures, which reduce the rate of crystallization, preventing the system from reaching equilibrium during the experimental duration (70 hours). In a few other cases (e.g., HLW07-07), the data show an abrupt change of slope, characteristic of the appearance of a second phase. Similar observations were noted previously in the testing of Phase 1 glasses [2]. In spite of these observations, it is straightforward 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 (see Table 4.12 and Appendix A).

Overall, $T_{1\%}$ could be estimated for 39 of the 40 Phase 2 matrix glasses; HLW07-36 did not show sufficient crystallization (≤ 0.3 vol%) even at low temperatures to allow estimation of $T_{1\%}$. The 39 estimated $T_{1\%}$ values show a fairly wide range of 750.0°C to 1317.0°C, which can be compared with the range of 554.2°C to 1301.2°C found for the Phase 1 $T_{1\%}$-modeling study, which included a total of 167 glasses [1, 2]. The median $T_{1\%}$ is 978.1°C, which can be compared with the WTP processing requirement of $T_{1\%} \leq 950$°C. The most prevalent crystalline phase is spinel, as expected, especially for the replicates and the inner-layer glasses. Heat-treated glasses from the outer-layer show a good deal more variation in the major crystalline phases. In addition to spinel, zircon, zirconium oxide, thorium oxide, and strontium phosphate are also observed (Table 4.12).

Figure 4.6 shows that the estimated $T_{1\%}$ values are distributed rather evenly within the temperature range of 750°C to 1300°C. In spite of the property constraint of spinel $T_{1\%} < 1000$°C imposed on the matrix design, 12 glasses have an estimated $T_{1\%}$ above 1050°C. This is, however, primarily due to the fact that most of these glasses crystallize non-spinel phases during heat treatment. In fact, the highest spinel $T_{1\%}$ value determined for the Phase 2 glasses (excluding replicate) is 1059.3°C, supporting the effectiveness of the spinel $T_{1\%}$ constraint in the matrix design. Most glasses with high estimated $T_{1\%}$ values are from the outer layer of the matrix and have zirconia or thoria as the major crystalline phase. A similar result was found in the Phase 1 study [1, 2]. There continues to be a relative paucity of $T_{1\%}$ data for Zr- and Th-related phases around 950°C. For comparison, only three glasses with estimated $T_{1\%}$ values below 1000°C exhibit non-spinel major crystalline phases.

Table 4.13 lists the replicates in the Phase 2 matrix and the replicated original from the Phase 1 matrices (i.e., glasses from the HLW02- and HLW03- series), the corresponding estimated $T_{1\%}$ values, and pairwise standard deviations (SDs). The pooled SD is calculated to be 29.94°C, which shows that the current tests were subject to slightly larger variation than the Phase 1 modeling tests (pooled SD = 26.06°C [1]). This is, however, consistent with the considerably longer duration involved with testing of the current replicate pairs (over 3 years).

SECTION 5
SUMMARY

In order to augment and improve Phase 1 IHLW property-composition models [1, 2], a 2-layered statistical design was used to develop the Phase 2 matrix of HLW glass formulations for testing. A total of 40 Phase 2 matrix glasses including a center glass of the inner layer, 20 outer-layer glasses, 15 inner-layer glasses, and 4 replicate glasses (of Phase 1 glasses previously studied) were generated to cover the EGCR. After completion of the design at PNWD, the 40 Phase 2 matrix glasses were prepared and tested at VSL, following an approach similar to one that was used previously in model development [1, 2].

Although target glass compositions are used in modeling, XRF was used to provide confirmatory analysis of the compositions of the prepared glasses. The analyzed compositions generally agree well with the target compositions. Discrepancies for selected minor components (e.g., barium) were traced to spectral interferences in the XRF analysis.

The HLW Phase 2 matrix glasses were subjected to the 7-day PCT at 90°C. The PCT data confirm the observation from Phase 1 study that most glasses in the EGCR are unlikely to exhibit PCT responses that approach or exceed the reference glass (DWPF-EA) limits. The measured PCT releases are distributed mostly around the low-release regions: 0.192 g/l to 6.065 g/l for boron, 0.321 g/l to 4.561 g/l for lithium, and 0.071 g/l to 4.768 g/l for sodium. Since the PCT results from the Phase 2 matrix glasses do not fall in the general area of high releases, the relative paucity of data for high PCT releases (e.g., PCT B releases > 5 g/l) will continue to be a potential limitation for the Phase 2 model development. Testing of replicate glass pairs suggest that the agreement between the replicates is generally comparable to (or, in the case of boron, better than) those from Phase 1 tests [1, 2], in spite of the longer time period that covers the testing of the current replicate pairs.

In addition to the 40 Phase 2 matrix glasses, 10 glasses selected from the Phase 1 matrix were characterized with respect to melt viscosity and electrical conductivity. The measured viscosity and electrical conductivity data were fitted to the respective Vogel-Fulcher equations in order to obtain these property values at standard temperatures. The fitted viscosity values for the Phase 2 matrix glasses range from 8.04 P to 278.64 P, with a median of 80.92 P (min = 7.31 P, max = 278.64 P, and median = 55.36 P when the 10 Phase 1 glasses are included). The fitted electrical conductivity values for the Phase 2 matrix range from 0.112 S/cm to 0.981 S/cm, with a median of 0.243 S/cm (min = 0.112 S/cm, max = 0.981 S/cm, and median = 0.334 S/cm when the 10 Phase 1 glasses are included). The measured viscosities around the high end (i.e. > 150 P) are found to greatly exceed the predicted values. This suggests that the current viscosity model may require improvement in this region.

The HLW Phase 2 glasses also underwent isothermal heat treatment and measurement of crystal content. Regression of the heat-treatment data then provided estimates of $T_{1\%}$. Overall,

$T_{1\%}$ values could be estimated for 39 of the 40 glasses. Spinel was the most prevalent crystalline phase observed, especially for the inner-layer, with the highest *spinel* $T_{1\%}$ estimated to be 1059.3°C. When the non-spinel phases are included, the range of $T_{1\%}$ is 750.0°C to 1317.0 °C. This can be compared with the range of 554.2°C to 1481.4 °C for the Phase 1 $T_{1\%}$-modeling study [1, 2]. The major non-spinel phases observed are thorium oxide, zirconium oxide, zircon, and strontium phosphate. The relative standard deviation of $T_{1\%}$ determination pooled over four replicate pairs is 29.94°C.

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) [15]. This program is supplemented by a Quality Assurance Project Plan for RPP-WTP work performed at VSL [16]. 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 [17].

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.

SECTION 7
REFERENCES

[1] Kot, W. K., Gan, H., Feng, Z., Perez-Cardenas, F., Pegg, I. L., Cooley, S. K., and Piepel, G. F., "Development of Phase 1 IHLW Models for PCT Response and One-Percent Crystal Fraction Temperature ($T_{1\%}$)," Final Report, VSL-05R5780-1, Rev. 0, Vitreous State Laboratory, The Catholic University of America, Washington, D. C., April 12, 2005.

[2] Kot, W. K., Gan, H., and Pegg, I. L., "Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development," Final Report, VSL-05R5780-2, Rev. 0, Vitreous State Laboratory, The Catholic University of America, Washington, D. C., October 12, 2005.

[3] Swanberg, D. J., "HLW Glass Property Composition Modeling," BNI Test Specification, 24590-HLW-TSP-RT-01-006, Rev. 1, River Protection Project, Waste Treatment Plant, Richland, WA, November 27, 2001.

[4] Gan, H. and Pegg, I. L., "HLW Glass Property Composition Modeling," Test Plan, VSL-02T7800-1, Rev. 1, Vitreous State Laboratory, The Catholic University of America, Washington, D. C., April 16, 2002.

[5] Westsik, Jr., J. H., WTP Test Exception, 24590-WTP-TEF-RT-03-078, Rev. 0, River Protection Project, Waste Treatment Plant, Richland, WA, December 10, 2003.

[6] Kot, W. K., Klatt, K., Gan, H., Pegg, I. L., Cooley, S. K., Piepel, G. F., and Bates, D. J., "Regulatory Testing of RPP-WTP HLW Glass to Support Delisting Compliance," Final Report, VSL-04R4780-1, Rev. 0, Vitreous State Laboratory, The Catholic University of America, Washington, D. C., September 30, 2004.

[7] Gan, H., Feng, Z., and Pegg, I. L., "Summary and Recommendations on Viscosity and Conductivity Model Forms to Support HLW Vitrification," Letter Report, VSL-04-L4780-1, Rev. 0, Vitreous State Laboratory, The Catholic University of America, Washington, D.C., September 8, 2004.

[8] "Updated HLW compositions with ACM data," e-mail message, Vienna, J. D. to Pegg, I. L., November 14, 2005.

[9] U.S. Department of Energy, Office of River Protection, "Design, Construction, and Commissioning of the Hanford Tank Waste Treatment and Immobilization Plant," Contract Number: DE-AC27-01RV14136, 2001.

[10] Vitreous State Laboratory, "Crucible Melts," Technical Procedure TPC-CM, Rev. 1, Vitreous State Laboratory, The Catholic University of America, D. C., July 10, 2002.

[11] Kot, W. K. and Pegg, I. L., "Glass Formulation and Testing with RPP-WTP HLW Simulants," Final Report, VSL-01R2540-2, Rev. 0, Vitreous State Laboratory, The Catholic University of America, Washington, D. C., February 16, 2001.

[12] Fu, S. S., and Pegg, I. L., "Glass Formulation and Testing with TWRS HLW Simulants," Final Report, Vitreous State Laboratory, The Catholic University of America, Washington, DC, January 18, 1998.

[13] "Standard Test Methods for Determining Chemical Durability of Nuclear, Hazardous, and Mixed Waste Glasses: The Product Consistency Test," ASTM C1285-97, American Society for Testing and Materials, West Conshohocken, PA, March 1998.

[14] Jantzen, C. M., Bibler, N. E., Beam, D. C., Crawford, C. L., and Pickett, M. A., "Characterization of the Defense Waste Processing Facility (DWPF) Environmental Assessment (EA) Glass Standard Reference Material," WSRC-TR-92-346, Westinghouse Savannah River Company, Aiken, SC, June, 1993.

[15] DOE/RW-0333P, "Quality Assurance Requirements and Description (QARD)," Rev. 13, Department of Energy, Office of Civilian Radioactive Waste Management, Washington D.C., 2004.

[16] VSL, "Quality Assurance Project Plan for RPP-WTP Support Activities Conducted by VSL," QAPP Rev. 8, Vitreous State Laboratory, The Catholic University of America, Washington, DC, June 2, 2005.

[17] VSL, "Master List of Controlled VSL Manuals and Standard Operating Procedures in Use," QA-MLCP, Rev. 15, Vitreous State Laboratory, The Catholic University of America, Washington, DC, June 6, 2005.

Table 2.1. Observation of Property Values Distributions for HLW Glasses in Phase 1 Studies.

Property	Distribution Peak (Range)	Data Deficient Location	Data Needed for Better Coverage of Property Values
Spinel $T_{1\%}$	About 950ºC (650 ºC to 1300ºC)	None apparent	Not specific
Zr- and Th-Related $T_{1\%}$	Data scattered (750 ºC to 1500ºC)	Around 950ºC	Data around 850ºC, 950ºC, and 1000ºC
Viscosity[a]	10 P to 20 P (10 P to 190 P)	Around 50 P to 80 P	Data around 50 P to 80 P
Electrical Conductivity[a]	About 0.3 S/cm (0.1 S/cm to 0.8 S/cm)	Around 0.4 S/cm to 0.44 S/cm	Data around 0.4 S/cm and 0.55 S/cm
PCT B (g/l)[b]	About 0.5 g/l (0.02 g/l to 4.5 g/l, 2 around 12 g/l)	5 g/l to 16.7 g/l	Data around 5 g/l to 11 g/l

[a] No data from the Non-Spinel Matrix (HLW05) and Spinel Matrix (HLW06).
[b] No data from the Non-Spinel Matrix (HLW05).

Table 2.2. Design Variables and Their Lower and Upper Bounds in Phase 1 and Phase 2 Studies.

Component	Phase 2 Inner Layer		Phase 2 Outer Layer		Phase 1 Existing Glasses[(a)]	
	Lower Limit (wt%)	Upper Limit (wt%)	Lower Limit (wt%)	Upper Limit (wt%)	Minimum (wt%)	Maximum (wt%)
Al_2O_3	5	10	3	11.5	1.88	13
B_2O_3	8	11	6	13	4.3	15
Cr_2O_3	0.15	0.4	0.05	0.6	0	0.6
Fe_2O_3	6	11	4	14	1.4	15
Li_2O	1	3.5	0	4.5	0	6.01
MnO	2.5	4	0.5	6	0	8
Na_2O	10	14	6	18	3.7	20
NiO	0.2	0.65	0	1	0	1
SiO_2	40	47	35	51	33	53.1
SrO	2.5	7	0	10	0	10.29
ThO_2	1	3.5	0	4.4	0	6
UO_3	1.5	3	0	4.1	0	6.5
ZnO	0.5	1.5	0	2.5	0	4
ZrO_2	2.5	6.5	1	9.6	0	11.5
Others1	0	1.36	0	1.36	—[(b)]	—[(b)]
Others2	0	1.24	0	2.48	—[(b)]	—[(b)]
Constant	1.74	1.74	3.48	3.48	—[(b)]	—[(b)]

[(a)] Includes 167 HLW glasses from 4 different Phase 1 matrices.
[(b)] — indicates empty data field; oxides grouping for these components are different for different matrices.

Table 2.3. Definition of "Others1" Component for HLW Phase 2 Study.

Oxide	Composition (wt%)	Maximum in Glass (wt%)	Basis for Maximum in Glass
MoO_3	28.68	0.39	S8.1[(a)]
P_2O_5	47.06	0.64	G2 & actual waste[(b)]
SO_3	24.26	0.33	G2 & actual waste
Sum	100.00	1.36	NA[(c)]

[(a)] "S8.1" refers to Specification 8.1 in Section C of the WTP Contract [9].
[(b)] "G2 & actual waste" refers to calculations made with WTP dynamic simulation flow-sheet (G2) for actual waste compositions.
[(c)] NA = Not applicable.

Table 2.4. Definition of "Others2" Component for HLW Phase 2 Study.

Oxide	Composition (wt%)	Maximum in Glass (wt%)	Basis for Maximum in Glass
CdO	40.32	1.00	Max (1.39) hit previously[(a)]
CoO	9.27	0.23	S8.1[(b)]
CuO	9.68	0.24	S8.1
PbO	40.73	1.01	G2 & actual waste[(c)]
Sum	100.00	2.48	NA[(d)]

(a) The maximum value of interest was achieved previously in Phase 1 study.
(b) "S8.1" refers to Specification 8.1 in Section C of the WTP Contract [9].
(c) "G2 & actual waste" refers to calculations made with WTP dynamic simulation flow-sheet (G2) for actual waste compositions.
(d) NA = Not applicable.

Table 2.5. Definition of "Constant" Component for HLW Phase 2 Study.

Oxide	Intended Composition (wt%)	Intended Maximum in Glass on Outer Layer (wt%)	Actual[(a)] Composition (wt%)	Actual[(a)] Maximum in Glass on Outer Layer (wt%)	Basis for Maximum in Glass
CaO	8.62	0.30	8.65	0.30	max (0.8) hit previously[(b)]
Ce_2O_3	10.92	0.38	10.95	0.38	S8.1[(c)]
Cl	9.77	0.34	9.80	0.34	G2 & actual waste[(d)]
Cs_2O	7.18	0.25	7.20	0.25	S8.1
F	3.45	0.12	3.46	0.12	G2 & actual waste
K_2O	16.67	0.58	16.71	0.58	G2 & actual waste
La_2O_3	7.18	0.25	7.20	0.25	max (1.22) hit previously[(b)]
Pr_2O_3	4.60	0.16	4.61	0.16	S8.1
Rb_2O	2.30	0.08	2.31	0.08	S8.1
Rh_2O_3	2.30	0.08	2.31	0.08	G2 & actual waste
RuO_2	2.87	0.10	2.88	0.10	G2 & actual waste
Sb_2O_3	11.49	0.40	11.53	0.40	S8.1
SnO_2	6.61	0.23	6.63	0.23	G2 & actual waste
Ta_2O_5	0.29	0.01	0.00[(d)]	0.00[(d)]	S8.1
WO_3	3.45	0.12	3.46	0.12	S8.1
Y_2O_3	2.30	0.08	2.30	0.08	S8.1
Sum	100.00	3.48	100.00	3.47	NA[(e)]

(a) Ta_2O_5 was inadvertently omitted from the compositions of the Phase 2 matrix; it was not included in the actual glass melted.
(b) The maximum value of interest was achieved previously in Phase 1 study.
(c) "S8.1" refers to Specification 8.1 in Section C of the WTP Contract [9].
(d) "G2 & actual waste" refers to calculations made with WTP dynamic simulation flow-sheet (G2) for actual waste compositions.
(e) NA = Not applicable.

Table 2.6. Oxides Excluded from HLW Phase 2 Study.

Oxide	Composition in Phase 2 (wt %)	Basis for Exclusion[a]
Ag_2O	0	max (0.2) hit previously
As_2O_5	0	max (0.22) hit previously
BaO	0	max (0.1) hit previously
Bi_2O_3	0	max (0.05) hit previously
MgO	0	max (1.39) approached (1.36) previously
Nd_2O_3	0	max (0.79) hit previously
PdO	0	max (0.11) hit previously
SeO_2	0	max (0.4) hit previously
TeO_2	0	max (0.07) hit previously
TiO_2	0	max (0.15) hit previously
Tl_2O	0	max (0.19) hit previously
V_2O_5	0	max (0.03) hit previously

[a] The maximum value of interest was achieved or approached previously in Phase 1 study.

Table 2.7. Glass Property Constraints for the HLW Phase 2 Matrix and the Property-Composition Models Used for Their Implementation.

Property	Property-Composition Model	Lower Limit	Upper Limit
Viscosity at 1150°C (η_{1150})	Model 16 in Table 8 of Reference [7]	10 P[(a)]	100 P
Electrical Conductivity at 1150°C (σ_{1150})	Model 5 in Table 10 of Reference [7]	0.2 S/cm	0.7 S/cm[(b)]
Spinel $T_{1\%}$	Model in Table 6.8 of Reference [2]	None	1000°C
Th- and Zr-Related $T_{1\%}$-	NA[(c)]	None	None
Normalized PCT B Release	NA	None	None

[(a)] Not achieved for the Phase 2 inner layer (minimum predicted viscosity = 13.34 P).
[(b)] Not achieved for the Phase 2 inner layer (maximum predicted electrical conductivity = 0.463 S/cm).
[(c)] NA = Not applicable.

Table 2.8. 18-Component Target Glass Compositions (wt%) for the HLW Phase 2 Test Matrix Glasses.

Glass ID	Point Type[a]	Melt Order	Al_2O_3	B_2O_3	Cr_2O_3	Fe_2O_3	Li_2O	MnO	Na_2O	NiO	SiO_2	SrO	ThO_2	UO_3	ZnO	ZrO_2	Others1	Others2	Constant	Remain-ing	Sum[b]
HLW07-01	C	20	7.161	9.206	0.277	7.993	1.802	3.171	11.287	0.422	41.825	4.260	2.138	2.206	0.983	4.300	0.644	0.588	1.735	0.000	100.00
HLW07-02	R	6	5.500	9.149	0.040	10.001	3.701	3.500	9.001	0.800	49.003	1.500	0.000	0.000	2.000	2.500	0.600	0.610	1.348	0.746	100.00
HLW07-03	R	26	3.888	8.732	0.140	6.939	3.710	2.698	9.093	0.395	43.059	2.705	3.658	3.032	1.920	6.767	0.599	0.427	1.395	0.843	100.00
HLW07-04	R	34	8.500	14.000	0.020	9.500	6.000	0.000	4.000	0.100	53.000	0.080	0.000	0.000	2.000	0.000	0.600	0.110	1.498	0.592	100.00
HLW07-05	R	33	4.961	4.961	0.496	13.891	4.750	6.945	11.693	0.100	39.825	0.000	0.000	6.306	3.461	0.000	0.598	0.110	1.313	0.590	100.00
HLW07-06	O	37	11.501	6.001	0.600	4.000	0.000	6.001	12.530	0.000	35.004	10.001	0.000	4.100	0.000	2.951	1.360	2.480	3.470	0.000	100.00
HLW07-07	O	1	3.000	6.001	0.050	14.001	0.000	0.500	17.977	1.000	35.059	10.001	0.000	4.100	0.000	1.000	1.360	2.480	3.470	0.000	100.00
HLW07-08	O	21	11.501	6.001	0.050	5.667	0.000	6.001	18.002	0.000	35.307	0.000	4.400	0.000	0.000	9.601	0.000	0.000	3.470	0.000	100.00
HLW07-09	O	32	3.000	6.001	0.600	10.459	4.500	0.500	8.603	0.000	35.004	10.001	4.400	0.000	2.500	9.601	1.360	0.000	3.470	0.000	100.00
HLW07-10	O	7	3.000	11.867	0.600	14.001	0.000	0.500	9.461	0.114	35.004	10.001	4.400	4.100	0.000	1.000	0.000	2.480	3.470	0.000	100.00
HLW07-11	O	10	11.501	6.001	0.600	10.495	4.500	0.500	17.016	1.000	35.004	2.332	0.000	4.100	0.000	1.000	0.000	2.480	3.470	0.000	100.00
HLW07-12	O	4	11.501	6.001	0.116	13.191	4.413	0.500	17.903	0.000	35.004	0.000	4.400	0.000	2.500	1.000	0.000	0.000	3.470	0.000	100.00
HLW07-13	O	3	11.501	6.001	0.600	4.000	0.790	0.500	18.002	0.000	36.494	0.000	0.000	4.100	2.500	9.601	1.360	1.080	3.470	0.000	100.00
HLW07-14	O	8	11.501	6.001	0.050	4.647	4.284	0.500	6.001	1.000	35.004	10.001	0.000	4.100	0.000	9.601	1.360	2.480	3.470	0.000	100.00
HLW07-15	O	9	4.400	6.001	0.050	4.000	0.000	6.001	18.002	1.000	35.004	10.001	0.000	2.470	0.000	9.601	0.000	0.000	3.470	0.000	100.00
HLW07-16	O	2	4.400	11.569	0.600	4.000	3.853	6.001	18.002	1.000	35.004	0.000	0.000	0.000	2.500	9.601	0.000	0.000	3.470	0.000	100.00
HLW07-17	O	12	11.501	13.001	0.050	4.000	4.253	6.001	18.002	0.000	35.861	0.000	0.000	0.000	0.000	2.500	1.360	0.000	3.470	0.000	100.00
HLW07-18	O	15	9.077	13.001	0.600	7.925	4.500	0.500	18.002	0.000	37.524	0.000	4.400	0.000	0.000	1.000	0.000	0.000	3.470	0.000	100.00
HLW07-19	O	25	3.000	6.572	0.600	5.401	4.210	0.500	15.061	0.000	35.004	10.001	0.000	4.100	0.000	9.601	0.000	2.480	3.470	0.000	100.00
HLW07-20	O	18	11.501	13.001	0.600	5.501	4.500	6.001	6.001	0.000	46.179	0.000	2.246	0.000	0.000	1.000	0.000	0.000	3.470	0.000	100.00
HLW07-21	O	19	3.000	6.001	0.050	5.401	0.000	0.500	11.335	0.000	42.700	10.001	0.000	4.100	0.000	9.601	1.360	2.480	3.470	0.000	100.00
HLW07-22	O	17	11.501	6.073	0.050	4.000	0.000	0.500	12.419	1.000	35.004	10.001	4.400	4.100	2.500	2.500	0.000	2.480	3.470	0.000	100.00
HLW07-23	O	35	4.400	13.001	0.600	4.000	1.822	0.500	6.620	1.000	41.883	6.501	0.000	4.100	2.500	9.601	0.000	0.000	3.470	0.000	100.00
HLW07-24	O	23	11.501	13.001	0.600	5.501	0.000	0.500	16.120	1.000	37.445	0.000	4.400	4.100	0.000	1.000	1.360	0.000	3.470	0.000	100.00
HLW07-25	O	22	11.501	6.001	0.050	5.501	0.997	6.001	11.453	0.000	42.662	0.000	4.400	4.100	0.384	1.000	0.000	2.480	3.470	0.000	100.00

[a] C = Center Point, R = Replicate, O = Outer Layer, and I = Inner Layer.
[b] The wt% values are rounded to three decimal places and may not sum to 100.000 exactly.

Table 2.8. 18-Component Target Glass Compositions (wt%) for the HLW Phase 2 Test Matrix Glasses (continued).

Glass ID	Point Type[a]	Melt Order	Al_2O_3	B_2O_3	Cr_2O_3	Fe_2O_3	Li_2O	MnO	Na_2O	NiO	SiO_2	SrO	ThO_2	UO_3	ZnO	ZrO_2	Others1	Others2	Constant	Remain-ing	Sum[b]
HLW07-26	I	14	10.001	8.000	0.150	6.000	3.460	2.500	10.001	0.650	47.002	2.500	3.500	1.500	0.500	2.500	0.000	0.000	1.735	0.000	100.00
HLW07-27	I	39	10.001	11.001	0.400	6.000	3.500	2.500	10.001	0.200	40.002	7.000	1.000	3.000	0.500	2.500	0.660	0.000	1.735	0.000	100.00
HLW07-28	I	30	10.001	8.000	0.150	6.000	3.500	2.500	14.001	0.650	40.002	3.100	3.500	1.500	1.500	2.500	1.360	0.000	1.735	0.000	100.00
HLW07-29	I	40	5.000	11.001	0.150	11.001	1.000	4.000	10.782	0.650	40.002	5.179	3.500	3.000	0.500	2.500	0.000	0.000	1.735	0.000	100.00
HLW07-30	I	11	5.000	8.000	0.400	11.001	1.000	3.687	12.614	0.200	47.002	2.500	1.000	1.500	0.500	2.500	1.360	0.000	1.735	0.000	100.00
HLW07-31	I	36	10.001	11.001	0.400	6.000	1.357	2.500	10.001	0.403	40.002	7.000	1.000	3.000	0.500	2.500	1.360	1.240	1.735	0.000	100.00
HLW07-32	I	5	5.000	8.000	0.150	11.001	1.000	2.500	14.001	0.650	40.002	3.264	1.000	1.500	1.096	6.500	1.360	1.240	1.735	0.000	100.00
HLW07-33	I	27	10.001	8.000	0.400	6.297	1.000	4.000	12.268	0.650	42.207	6.940	1.000	1.500	1.500	2.500	0.000	0.000	1.735	0.000	100.00
HLW07-34	I	31	10.001	11.001	0.150	6.000	2.063	4.000	10.001	0.650	41.514	2.905	1.000	1.981	0.500	6.500	0.000	0.000	1.735	0.000	100.00
HLW07-35	I	38	10.001	9.587	0.400	6.000	1.347	2.500	10.001	0.200	40.002	7.000	3.500	1.500	1.500	4.727	0.000	0.000	1.735	0.000	100.00
HLW07-36	I	24	9.500	11.001	0.150	6.000	1.000	2.500	14.001	0.200	40.002	6.910	1.000	3.000	0.500	2.500	0.000	0.000	1.735	0.000	100.00
HLW07-37	I	13	5.000	8.000	0.150	10.501	3.500	4.000	13.811	0.200	40.002	2.500	3.500	1.500	0.500	2.500	1.360	1.240	1.735	0.000	100.00
HLW07-38	I	28	5.000	11.001	0.400	6.500	1.000	4.000	10.393	0.200	41.670	2.500	3.500	1.500	1.500	6.500	1.360	1.240	1.735	0.000	100.00
HLW07-39	I	16	5.500	11.001	0.400	6.000	1.000	2.500	13.629	0.200	44.794	2.500	1.000	1.500	0.500	6.500	0.000	1.240	1.735	0.000	100.00
HLW07-40	I	29	5.000	8.000	0.400	10.384	1.000	2.500	10.001	0.200	42.803	7.000	3.500	2.119	1.500	2.617	0.000	1.240	1.735	0.000	100.00

[a] C = Center Point, R = Replicate, O = Outer Layer, and I = Inner Layer.
[b] The wt% values are rounded to three decimal places and may not sum to 100.000 exactly.

Table 2.9 Composition (wt%)[(a)] Expansions of Others1, Others2, and Constant Components for the HLW Phase 2 Test Matrix Glasses in Table 2.8.

Glass ID	Others1 Components			Others2 Components				Constant Components															
	MoO_3	P_2O_5	SO_3	CdO	CoO	CuO	PbO	CaO	Ce_2O_3	Cl	Cs_2O	F	K_2O	La_2O_3	Pr_2O_3	Rb_2O	Rh_2O_3	RuO_2	Sb_2O_3	SnO_2	Ta_2O_5	WO_3	Y_2O_3
HLW07-01	0.185	0.303	0.156	0.237	0.055	0.057	0.240	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-02	0.000	0.500	0.100	0.500	0.010	0.020	0.080	0.500	0.048	0.200	0.010	0.050	0.060	0.300	0.000	0.000	0.050	0.080	0.050	0.000	0.000	0.000	0.000
HLW07-03	0.000	0.499	0.100	0.200	0.010	0.043	0.174	0.499	0.048	0.200	0.010	0.050	0.060	0.299	0.000	0.000	0.050	0.080	0.100	0.000	0.000	0.000	0.000
HLW07-04	0.000	0.500	0.100	0.050	0.010	0.010	0.040	0.500	0.048	0.200	0.010	0.050	0.060	0.300	0.000	0.000	0.050	0.080	0.200	0.000	0.000	0.000	0.000
HLW07-05	0.000	0.498	0.100	0.050	0.010	0.010	0.040	0.498	0.048	0.199	0.010	0.050	0.060	0.299	0.000	0.000	0.050	0.080	0.020	0.000	0.000	0.000	0.000
HLW07-06	0.390	0.640	0.330	1.000	0.230	0.240	1.010	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-07	0.390	0.640	0.330	1.000	0.230	0.240	1.010	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-08	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-09	0.390	0.640	0.330	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-10	0.000	0.000	0.000	1.000	0.230	0.240	1.010	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-11	0.000	0.000	0.000	1.000	0.230	0.240	1.010	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-13	0.390	0.640	0.330	0.435	0.100	0.105	0.440	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-14	0.390	0.640	0.330	1.000	0.230	0.240	1.010	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-17	0.390	0.640	0.330	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-19	0.000	0.000	0.000	1.000	0.230	0.240	1.010	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-21	0.390	0.640	0.330	1.000	0.230	0.240	1.010	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-22	0.000	0.000	0.000	1.000	0.230	0.240	1.010	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-24	0.390	0.640	0.330	0.000	0.000	0.000	0.000	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080
HLW07-25	0.000	0.000	0.000	1.000	0.230	0.240	1.010	0.300	0.380	0.340	0.250	0.120	0.580	0.250	0.160	0.080	0.080	0.100	0.400	0.230	0.000	0.120	0.080

(a) For each glass, the sum of the wt% values for the components comprising Others1, Others2, and Constant equal the wt% values listed in the Others1, Others2, and Constant columns of Table 2.8, except for any differences resulting from rounding wt% values to three decimal places. The equalities are exact to the additional decimal places contained in the data base.

Table 2.9 Composition (wt%)[a] Expansions of Others1, Others2, and Constant Components for the HLW Phase 2 Test Matrix Glasses in Table 2.8 (continued).

Glass ID	Others1 Components			Others2 Components				Constant Components															
	MoO_3	P_2O_5	SO_3	CdO	CoO	CuO	PbO	CaO	Ce_2O_3	Cl	Cs_2O	F	K_2O	La_2O_3	Pr_2O_3	Rb_2O	Rh_2O_3	RuO_2	Sb_2O_3	SnO_2	Ta_2O_5	WO_3	Y_2O_3
HLW07-26	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-27	0.189	0.311	0.160	0.000	0.000	0.000	0.000	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-28	0.390	0.640	0.330	0.000	0.000	0.000	0.000	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-29	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-30	0.390	0.640	0.330	0.000	0.000	0.000	0.000	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-31	0.390	0.640	0.330	0.500	0.115	0.120	0.505	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-32	0.390	0.640	0.330	0.500	0.115	0.120	0.505	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-33	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-34	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-35	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-36	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-37	0.390	0.640	0.330	0.500	0.115	0.120	0.505	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-38	0.390	0.640	0.330	0.500	0.115	0.120	0.505	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-39	0.000	0.000	0.000	0.500	0.115	0.120	0.505	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040
HLW07-40	0.000	0.000	0.000	0.500	0.115	0.120	0.505	0.150	0.190	0.170	0.125	0.060	0.290	0.125	0.080	0.040	0.040	0.050	0.200	0.115	0.000	0.060	0.040

[a] For each glass, the sum of the wt% values for the components comprising Others1, Others2, and Constant equal the wt% values listed in the Others1, Others2, and Constant columns of Table 2.8, except for any differences resulting from rounding wt% values to three decimal places. The equalities are exact to the additional decimal places contained in the data base.

Table 2.10. Composition Expansions of Remaining Components for the HLW Phase 2 Test Matrix Glasses in Table 2.8.

Glass ID	Remaining Components (wt%)[a, b]											
	Ag_2O	As_2O_5	BaO	Bi_2O_3	MgO	Nd_2O_3	PdO	SeO_2	TeO_2	TiO_2	Tl_2O	V_2O_5
HLW07-01	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-02	0.040	0.046	0.060	0.010	0.120	0.000	0.120	0.150	0.010	0.030	0.140	0.020
HLW07-03	0.087	0.101	0.130	0.010	0.120	0.000	0.120	0.100	0.010	0.030	0.093	0.043
HLW07-04	0.020	0.023	0.030	0.010	0.120	0.000	0.120	0.200	0.010	0.030	0.019	0.010
HLW07-05	0.020	0.023	0.030	0.010	0.120	0.000	0.120	0.199	0.010	0.030	0.019	0.010
HLW07-06	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-07	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-08	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-09	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

[a] For each glass, the sum of the wt% values for the components comprising Remaining equals the wt% value listed in the Remaining column of Table 2.8, except for any differences resulting from rounding wt% values to three decimal places.

[b] These components are present only in glasses replicated from Phase 1 matrices (i.e., HLW07-02 through -05). They are not part of the design for the "new" Phase 2 glasses (i.e., HLW07-06 through -40) and are not present in those glasses. Full composition expansions are given for all glasses for the purpose of completeness and consistency with earlier modeling reports.

Table 2.10. Composition Expansions of Remaining Components for the HLW Phase 2 Test Matrix Glasses in Table 2.8 (continued).

Glass ID	Remaining Components (wt%)[a, b]											
	Ag_2O	As_2O_5	BaO	Bi_2O_3	MgO	Nd_2O_3	PdO	SeO_2	TeO_2	TiO_2	Tl_2O	V_2O_5
HLW07-26	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-27	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-28	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-29	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-31	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-32	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-33	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-34	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-35	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-36	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-37	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-38	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-39	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HLW07-40	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(a) For each glass, the sum of the wt% values for the components comprising Remaining equals the wt% value listed in the Remaining column of Table 2.8, except for any differences resulting from rounding wt% values to three decimal places.

(b) These components are present only in glasses replicated from Phase 1 matrices (i.e., HLW07-02 through -05). They are not part of the design for the "new" Phase 2 glasses (i.e., HLW07-06 through -40) and are not present in those glasses. Full composition expansions are given for all glasses for the purpose of completeness and consistency with earlier modeling reports.

Table 2.11. Phase 1 Matrix Glasses Selected for Viscosity and Electrical Conductivity Measurements and Their Compositions.

Oxide	HLW05-15	HLW05-20	HLW05-21	HLW05-22	HLW05-27
Ag_2O	0.100%	0.100%	0.100%	0.100%	0.100%
Al_2O_3	2.000%	13.000%	2.000%	13.000%	2.000%
B_2O_3	4.500%	14.000%	14.000%	14.000%	4.500%
BaO	0.500%	0.500%	0.500%	0.500%	0.500%
Bi_2O_3	0.200%	0.200%	0.200%	0.200%	0.200%
CaO	0.750%	0.750%	0.750%	0.750%	0.750%
CdO	0.050%	0.500%	0.050%	0.050%	0.500%
Cr_2O_3	0.250%	0.250%	0.250%	0.050%	0.050%
F	0.050%	0.050%	0.050%	0.050%	0.050%
Fe_2O_3	12.000%	1.500%	12.000%	2.500%	12.000%
K_2O	0.200%	0.200%	0.200%	0.200%	0.200%
La_2O_3	0.500%	0.500%	0.500%	0.500%	0.500%
Li_2O	0.000%	0.000%	0.000%	3.700%	5.950%
MgO	0.100%	0.100%	0.100%	0.100%	0.100%
MnO	0.100%	1.000%	0.100%	0.100%	1.000%
Na_2O	16.670%	20.000%	19.710%	6.500%	10.390%
NiO	0.050%	0.500%	0.050%	0.050%	0.500%
P_2O_5	0.300%	0.300%	0.300%	0.300%	0.300%
PbO	0.150%	0.150%	0.150%	0.150%	0.150%
PdO	0.020%	0.020%	0.020%	0.020%	0.020%
Rh_2O_3	0.040%	0.040%	0.040%	0.040%	0.040%
RuO_2	0.020%	0.020%	0.020%	0.020%	0.020%
SiO_2	49.000%	37.750%	34.000%	44.050%	45.610%
SO_3	0.100%	0.100%	0.100%	0.100%	0.100%
SrO	1.200%	1.200%	1.200%	1.200%	1.200%
ThO_2	1.500%	1.500%	6.000%	1.500%	1.500%
TiO_2	0.020%	0.020%	0.020%	0.020%	0.020%
Tl_2O	0.050%	0.050%	0.050%	0.050%	0.050%
UO_3	4.380%	1.000%	1.000%	6.500%	6.500%
ZnO	1.200%	1.200%	1.200%	1.200%	1.200%
ZrO_2	4.000%	3.500%	5.340%	2.500%	4.000%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

Table 2.11. Phase 1 Matrix Glasses Selected for Viscosity and Electrical Conductivity Measurements and Their Compositions (continued).

Oxide	HLW06-02	HLW06-04	HLW06-22	HLW06-32	HLW06-34
Ag_2O	0.100%	0.100%	0.100%	0.100%	0.100%
Al_2O_3	10.390%	8.000%	13.000%	1.880%	1.880%
B_2O_3	11.000%	6.500%	15.000%	15.000%	15.000%
BaO	0.300%	0.227%	0.000%	0.000%	0.000%
Bi_2O_3	0.300%	0.300%	0.300%	0.300%	0.300%
CaO	1.000%	0.757%	0.000%	0.000%	0.000%
CdO	0.235%	0.706%	1.646%	0.000%	0.000%
Cl	0.200%	0.200%	0.200%	0.200%	0.200%
Cr_2O_3	0.250%	0.250%	0.600%	0.600%	0.600%
F	0.440%	0.440%	0.440%	0.440%	0.440%
Fe_2O_3	7.000%	7.000%	1.400%	15.000%	1.400%
K_2O	1.640%	1.242%	0.000%	0.000%	0.000%
La_2O_3	0.176%	0.529%	1.234%	0.000%	0.000%
Li_2O	0.250%	0.250%	6.010%	0.000%	0.000%
MgO	1.170%	0.886%	0.000%	0.000%	0.000%
MnO	1.000%	1.000%	0.000%	8.000%	8.000%
Na_2O	20.000%	20.000%	6.840%	20.000%	20.000%
Nd_2O_3	0.329%	0.487%	0.802%	0.250%	0.250%
NiO	1.000%	0.600%	0.000%	0.000%	0.000%
P_2O_5	0.500%	0.500%	0.500%	0.500%	0.500%
PbO	0.910%	0.689%	0.000%	0.000%	0.000%
PdO	0.120%	0.120%	0.120%	0.120%	0.120%
Rh_2O_3	0.050%	0.050%	0.050%	0.050%	0.050%
RuO_2	0.130%	0.130%	0.130%	0.130%	0.130%
SiO_2	35.000%	35.000%	34.560%	37.430%	33.030%
SO_3	0.040%	0.120%	0.280%	0.000%	0.000%
SrO	1.470%	4.409%	10.287%	0.000%	0.000%
ThO_2	0.250%	1.500%	0.000%	0.000%	0.000%
TiO_2	1.000%	0.757%	0.000%	0.000%	0.000%
UO_3	0.750%	0.750%	6.500%	0.000%	6.500%
ZnO	1.500%	2.500%	0.000%	0.000%	0.000%
ZrO_2	1.500%	4.000%	0.000%	0.000%	11.500%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

Table 4.1 Compositional Analysis (wt%) of HLW Phase 2 Matrix Glasses by XRF.

Oxides	HLW07-01	HLW07-02	HLW07-03	HLW07-04	HLW07-05
Ag_2O	—[a]	0.06%	0.09%	0.03%	0.01%
Al_2O_3	7.77%	6.00%	4.40%	9.32%	5.43%
As_2O_5	—	0.01%	0.02%	—	—
B_2O_3	**9.21%**[b]	**9.15%**	**8.73%**	**14.00%**	**4.96%**
BaO	—	—	—	0.03%	0.03%
Bi_2O_3	—	—	0.02%	—	0.01%
CaO	0.18%	0.55%	0.53%	0.53%	0.54%
CdO	0.23%	0.49%	0.20%	—	—
Ce_2O_3	0.24%	0.03%	0.05%	0.05%	0.05%
Cl	0.16%	0.17%	0.18%	0.19%	0.14%
CoO	0.07%	0.02%	0.03%	0.03%	0.03%
Cr_2O_3	0.33%	0.05%	0.17%	0.03%	0.60%
Cs_2O	0.14%	0.01%	0.01%	0.01%	—
CuO	0.07%	0.03%	0.08%	0.02%	0.03%
F	—			—	
Fe_2O_3	7.63%	9.71%	6.88%	8.98%	13.25%
K_2O	0.39%	0.16%	0.15%	0.17%	0.13%
La_2O_3	0.05%	0.31%	0.30%	0.25%	0.26%
Li_2O	**1.80%**	**3.70%**	**3.71%**	**6.00%**	**4.75%**
MgO	—	—	—	—	—
MnO	3.23%	3.63%	2.87%	—	7.13%
MoO_3	0.24%	—	—	—	—
Na_2O	11.17%	9.11%	9.24%	4.39%	12.20%
NiO	0.40%	0.80%	0.40%	0.09%	0.09%
P_2O_5	0.37%	0.61%	0.61%	0.62%	0.58%
PbO	0.23%	0.07%	0.14%	0.03%	0.06%
PdO	—	0.10%	0.09%	0.10%	0.07%
Pr_2O_3	0.10%	—	—	—	—
Rb_2O	0.04%	—	—	—	—
Rh_2O_3	0.05%	0.05%	0.04%	0.05%	0.09%
RuO_2	0.04%	0.08%	0.03%	0.08%	0.05%
SO_3	0.20%	0.22%	0.16%	0.23%	0.27%
Sb_2O_3	0.23%	0.05%	0.09%	0.17%	0.01%
SeO_2	—	0.16%	0.15%	0.19%	0.16%
SiO_2	41.63%	48.41%	41.83%	52.27%	38.88%
SnO_2	0.13%	0.02%		0.02%	0.02%
SrO	4.13%	1.48%	2.76%	0.09%	0.02%
TeO_2	—	0.01%	—	—	0.02%
ThO_2	2.04%	—	3.67%	—	—
TiO_2	—	0.07%	0.05%	0.06%	0.04%
Tl_2O	—	—	0.08%	0.02%	—
UO_3	2.21%	—	3.19%	—	6.57%
V_2O_5	—	0.02%	0.04%	0.01%	—
WO_3	0.07%	—	—	—	—
Y_2O_3	0.06%	0.00%	—	—	—
ZnO	0.98%	2.04%	1.98%	1.88%	3.44%
ZrO_2	4.10%	2.42%	6.71%	0.00%	—
TOTAL	99.91%	99.79%	99.64%	99.94%	99.91%

[a] — indicates empty data field.
[b] 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 Phase 2 Matrix Glasses by XRF (continued).

Oxides	HLW07-06	HLW07-07	HLW07-08	HLW07-09	HLW07-10
Al_2O_3	11.75%	3.38%	11.95%	3.74%	3.61%
B_2O_3	**6.00%**[(a)]	**6.00%**	**6.00%**	**6.00%**	**11.87%**
CaO	0.34%	0.35%	0.34%	0.35%	0.33%
CdO	0.99%	1.07%	—	—	1.03%
Ce_2O_3	0.44%	0.49%	0.38%	0.45%	0.45%
Cl	0.29%	0.24%	0.37%	0.30%	0.28%
CoO	0.27%	0.31%	—	0.01%	0.29%
Cr_2O_3	0.67%	0.07%	0.06%	0.70%	0.69%
Cs_2O	0.29%	0.24%	0.25%	0.29%	0.31%
CuO	0.30%	0.33%	—	0.01%	0.31%
F	—[(b)]	—	—	—	—
Fe_2O_3	3.78%	14.13%	5.38%	10.20%	13.34%
K_2O	0.64%	0.65%	0.72%	0.70%	0.65%
La_2O_3	0.18%	0.20%	0.17%	0.20%	0.17%
Li_2O	—	—	—	**4.50%**	—
MnO	6.03%	0.54%	6.09%	0.51%	0.50%
MoO_3	0.51%	0.58%	0.02%	0.56%	0.03%
Na_2O	12.91%	17.15%	17.69%	8.25%	10.15%
NiO	—	1.04%	—	—	0.12%
P_2O_5	0.73%	0.70%	0.03%	0.69%	0.03%
PbO	0.96%	1.05%	—	—	0.97%
Pr_2O_3	0.21%	0.24%	0.18%	0.22%	0.22%
Rb_2O	0.08%	0.08%	0.10%	0.10%	0.08%
Rh_2O_3	0.13%	0.12%	0.08%	0.10%	0.13%
RuO_2	0.11%	0.10%	0.10%	0.11%	0.11%
SO_3	0.32%	0.48%	0.06%	0.36%	0.17%
Sb_2O_3	0.42%	0.43%	0.43%	0.35%	0.39%
SiO_2	34.90%	33.71%	35.74%	34.70%	34.02%
SnO_2	0.24%	0.28%	0.23%	0.26%	0.27%
SrO	9.48%	10.41%	0.02%	9.85%	9.80%
ThO_2	—	—	4.03%	4.29%	4.22%
UO_3	3.92%	4.32%	0.01%	—	4.22%
WO_3	0.13%	0.14%	0.14%	0.13%	0.14%
Y_2O_3	0.11%	0.11%	0.12%	0.12%	0.11%
ZnO	0.02%	0.04%	0.02%	2.56%	0.05%
ZrO_2	2.73%	0.99%	8.99%	9.11%	0.91%
TOTAL	99.86%	99.95%	99.68%	99.70%	99.94%

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

Table 4.1 Compositional Analysis (wt%) of HLW Phase 2 Matrix Glasses by XRF (continued).

Oxides	HLW07-11	HLW07-12	HLW07-13	HLW07-14	HLW07-15
Al_2O_3	11.32%	11.66%	11.77%	11.56%	4.69%
B_2O_3	**6.00%**[(a)]	**6.00%**	**6.00%**	**6.00%**	**6.00%**
CaO	0.34%	0.33%	0.35%	0.35%	0.33%
CdO	1.05%	—	0.43%	1.04%	—
Ce_2O_3	0.47%	0.40%	0.42%	0.42%	0.45%
Cl	0.29%	0.30%	0.30%	0.32%	0.27%
CoO	0.31%	0.01%	0.13%	0.30%	—
Cr_2O_3	0.75%	0.16%	0.68%	0.07%	0.07%
Cs_2O	0.29%	0.28%	0.29%	0.31%	0.26%
CuO	0.32%	0.01%	0.13%	0.32%	0.01%
F	—[(b)]	—	—	—	—
Fe_2O_3	10.45%	12.74%	3.95%	4.64%	4.08%
K_2O	0.65%	0.65%	0.66%	0.71%	0.66%
La_2O_3	0.18%	0.18%	0.16%	0.20%	0.18%
Li_2O	**4.50%**	**4.41%**	**0.79%**	**4.28%**	—
MnO	0.54%	0.51%	0.53%	0.54%	6.39%
MoO_3	—	0.02%	0.48%	0.60%	0.04%
Na_2O	17.53%	18.60%	18.40%	5.94%	17.33%
NiO	1.00%	0.00%	0.00%	1.02%	1.05%
P_2O_5	0.03%	0.04%	0.71%	0.69%	—
PbO	1.00%	—	0.43%	1.02%	0.01%
Pr_2O_3	0.21%	0.20%	0.19%	0.23%	0.22%
Rb_2O	0.07%	0.10%	0.08%	0.09%	0.09%
Rh_2O_3	0.14%	0.09%	0.10%	0.12%	0.11%
RuO_2	0.09%	0.11%	0.11%	0.11%	0.10%
SO_3	0.14%	0.21%	0.33%	0.34%	0.06%
Sb_2O_3	0.49%	0.43%	0.46%	0.49%	0.49%
SiO_2	33.58%	34.51%	36.11%	34.43%	33.39%
SnO_2	0.28%	0.26%	0.24%	0.27%	0.27%
SrO	2.40%	0.04%	0.03%	9.99%	10.28%
ThO_2	—	4.05%	0.04%	—	—
UO_3	4.30%	0.01%	3.91%	4.11%	2.62%
WO_3	0.14%	0.14%	0.12%	0.14%	0.14%
Y_2O_3	0.12%	0.11%	0.11%	0.11%	0.12%
ZnO	0.03%	2.48%	2.50%	0.02%	0.01%
ZrO_2	0.97%	0.95%	8.81%	8.97%	9.98%
TOTAL	99.95%	99.96%	99.74%	99.75%	99.70%

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

Table 4.1 Compositional Analysis (wt%) of HLW Phase 2 Matrix Glasses by XRF (continued).

Oxides	HLW07-16	HLW07-17	HLW07-018	HLW07-19	HLW07-20
Al_2O_3	4.79%	11.56%	9.56%	3.49%	11.75%
B_2O_3	**11.57%**[(a)]	**13.00%**	**13.00%**	**6.57%**	**13.00%**
CaO	0.35%	0.36%	0.32%	0.36%	0.33%
CdO	—[(b)]	—	—	1.04%	—
Ce_2O_3	0.48%	0.50%	0.43%	0.48%	0.42%
Cl	0.26%	0.26%	0.30%	0.25%	0.29%
CoO	—	0.00%	0.01%	0.30%	0.00%
Cr_2O_3	0.80%	0.07%	0.69%	0.79%	0.68%
Cs_2O	0.23%	0.25%	0.22%	0.22%	0.28%
CuO	—	0.00%	0.01%	0.34%	0.01%
F	—	—	—	—	—
Fe_2O_3	4.31%	4.27%	7.15%	5.51%	5.24%
K_2O	0.68%	0.69%	0.65%	0.68%	0.69%
La_2O_3	0.18%	0.19%	0.16%	0.21%	0.17%
Li_2O	**3.85%**	**4.25%**	**4.50%**	**4.21%**	**4.50%**
MnO	6.81%	6.68%	0.49%	0.56%	6.02%
MoO_3	0.03%	0.51%	0.01%	0.06%	0.01%
Na_2O	16.58%	17.08%	18.71%	14.48%	6.28%
NiO	1.14%	—	0.00%	—	—
P_2O_5	0.02%	0.71%	0.04%	0.01%	0.04%
PbO	—	0.01%	—	1.08%	—
Pr_2O_3	0.21%	0.20%	0.18%	0.22%	0.19%
Rb_2O	0.12%	0.11%	0.09%	0.09%	0.10%
Rh_2O_3	0.10%	0.08%	0.07%	0.10%	0.09%
RuO_2	0.10%	0.08%	0.08%	0.09%	0.10%
SO_3	0.05%	0.34%	0.10%	0.06%	0.07%
Sb_2O_3	0.45%	0.44%	0.38%	0.42%	0.40%
SiO_2	32.97%	35.08%	37.66%	33.29%	45.61%
SnO_2	0.25%	0.25%	0.21%	0.26%	0.24%
SrO	0.01%	0.02%	0.02%	10.33%	0.03%
ThO_2	—	—	3.80%	—	2.15%
UO_3	—	—	—	4.43%	0.00%
WO_3	0.15%	0.16%	0.13%	0.15%	0.14%
Y_2O_3	0.13%	0.11%	0.10%	0.12%	0.11%
ZnO	2.83%	0.02%	0.03%	0.02%	0.02%
ZrO_2	10.20%	2.59%	0.88%	9.51%	0.97%
TOTAL	99.64%	99.86%	99.98%	99.72%	99.95%

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

Table 4.1 Compositional Analysis (wt%) of HLW Phase 2 Matrix Glasses by XRF (continued).

Oxides	HLW07-21	HLW07-22	HLW07-23	HLW07-24	HLW07-25
Al_2O_3	3.53%	11.29%	5.19%	11.64%	11.84%
B_2O_3	**6.00%**[(a)]	**6.07%**	**13.00%**	**13.00%**	**6.00%**
CaO	0.35%	0.36%	0.36%	0.33%	0.33%
CdO	1.02%	1.07%	—	—	0.93%
Ce_2O_3	0.44%	0.40%	0.45%	0.45%	0.35%
Cl	0.28%	0.34%	0.36%	0.32%	0.32%
CoO	0.30%	0.30%	—	0.00%	0.28%
Cr_2O_3	0.06%	0.06%	0.67%	0.68%	0.06%
Cs_2O	0.27%	0.30%	0.28%	0.30%	0.27%
CuO	0.33%	0.32%	—	—	0.30%
F	—[(b)]	—	—	—	—
Fe_2O_3	5.40%	4.09%	3.93%	5.42%	5.19%
K_2O	0.66%	0.67%	0.74%	0.66%	0.67%
La_2O_3	0.19%	0.19%	0.17%	0.17%	0.16%
Li_2O	—	—	**1.82%**	—	**1.00%**
MnO	0.53%	0.56%	0.53%	0.54%	5.97%
MoO_3	0.57%	0.04%	0.04%	0.47%	0.03%
Na_2O	10.99%	11.83%	6.61%	15.61%	12.02%
NiO	—	1.06%	0.98%	0.99%	—
P_2O_5	0.70%	—	0.04%	0.74%	0.03%
PbO	1.03%	1.07%	—	—	0.90%
Pr_2O_3	0.24%	0.25%	0.20%	0.19%	0.18%
Rb_2O	0.10%	0.09%	0.08%	0.08%	0.07%
Rh_2O_3	0.11%	0.12%	0.11%	0.12%	0.11%
RuO_2	0.13%	0.12%	0.11%	0.12%	0.11%
SO_3	0.24%	0.04%	0.06%	0.22%	0.06%
Sb_2O_3	0.46%	0.51%	0.41%	0.48%	0.48%
SiO_2	41.35%	33.92%	41.54%	37.30%	42.57%
SnO_2	0.26%	0.25%	0.23%	0.26%	0.24%
SrO	10.09%	10.43%	6.10%	0.04%	0.03%
ThO_2	—	4.45%	—	4.36%	4.00%
UO_3	4.28%	4.33%	4.13%	4.24%	3.95%
WO_3	0.14%	0.13%	0.13%	0.13%	0.13%
Y_2O_3	0.12%	0.12%	0.11%	0.11%	0.11%
ZnO	0.02%	2.60%	2.45%	0.02%	0.38%
ZrO_2	9.55%	2.53%	8.83%	0.98%	0.89%
TOTAL	99.73%	99.89%	99.67%	99.96%	99.95%

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

Table 4.1 Compositional Analysis (wt%) of HLW Phase 2 Matrix Glasses by XRF (continued).

Oxides	HLW07-26	HLW07-27	HLW07-28	HLW07-29	HLW07-30
Al_2O_3	10.35%	10.63%	10.53%	5.66%	5.58%
B_2O_3	**8.00%**[(a)]	**11.00%**	**8.00%**	**11.00%**	**8.00%**
CaO	0.18%	0.18%	0.18%	0.18%	0.18%
CdO	—[(b)]	—	—	—	—
Ce_2O_3	0.22%	0.23%	0.23%	0.25%	0.20%
Cl	0.16%	0.16%	0.15%	0.16%	0.13%
CoO	—	—	—	0.01%	—
Cr_2O_3	0.18%	0.47%	0.18%	0.18%	0.48%
Cs_2O	0.14%	0.14%	0.14%	0.15%	0.15%
CuO	0.01%	0.01%	0.01%	—	0.01%
F	—	—	—	—	—
Fe_2O_3	5.85%	5.78%	5.71%	10.71%	10.91%
K_2O	0.41%	0.42%	0.40%	0.40%	0.41%
La_2O_3	0.05%	0.04%	0.03%	0.06%	0.05%
Li_2O	**3.46%**	**3.50%**	**3.50%**	**1.00%**	**1.00%**
MnO	2.58%	2.54%	2.56%	4.18%	3.86%
MoO_3	0.02%	0.26%	0.49%	0.03%	0.51%
Na_2O	10.14%	10.17%	13.89%	10.31%	12.43%
NiO	0.64%	0.19%	0.64%	0.62%	0.20%
P_2O_5	0.03%	0.37%	0.74%	0.04%	0.75%
PbO	—	—	—	—	—
Pr_2O_3	0.10%	0.12%	0.10%	0.12%	0.10%
Rb_2O	0.05%	0.04%	0.04%	0.04%	0.04%
Rh_2O_3	0.05%	0.06%	0.06%	0.07%	0.05%
RuO_2	0.05%	0.06%	0.04%	0.07%	0.04%
SO_3	0.07%	0.20%	0.34%	0.12%	0.28%
Sb_2O_3	0.19%	0.18%	0.22%	0.18%	0.26%
SiO_2	46.30%	39.52%	39.73%	39.26%	46.04%
SnO_2	0.13%	0.13%	0.13%	0.14%	0.14%
SrO	2.54%	6.66%	3.01%	5.23%	2.48%
ThO_2	3.43%	0.92%	3.35%	3.46%	0.98%
UO_3	1.52%	3.00%	1.52%	3.12%	1.53%
WO_3	0.06%	0.07%	0.06%	0.09%	0.07%
Y_2O_3	0.06%	0.05%	0.06%	0.06%	0.06%
ZnO	0.53%	0.50%	1.48%	0.54%	0.54%
ZrO_2	2.44%	2.31%	2.38%	2.44%	2.46%
TOTAL	99.94%	99.91%	99.90%	99.87%	99.90%

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

Table 4.1 Compositional Analysis (wt%) of HLW Phase 2 Matrix Glasses by XRF (continued).

Oxides	HLW07-31	HLW07-32	HLW07-33	HLW07-34	HLW07-35
Al_2O_3	10.54%	5.42%	10.32%	10.57%	10.65%
B_2O_3	**11.00%**[(a)]	**8.00%**	**8.00%**	**11.00%**	**9.59%**
CaO	0.17%	0.19%	0.18%	0.18%	0.17%
CdO	0.47%	0.51%	—	—	—
Ce_2O_3	0.20%	0.23%	0.21%	0.21%	0.20%
Cl	0.16%	0.15%	0.17%	0.16%	0.18%
CoO	0.14%	0.05%	0.00%	—	0.00%
Cr_2O_3	0.43%	0.22%	0.49%	0.17%	0.44%
Cs_2O	0.15%	0.15%	0.15%	0.15%	0.14%
CuO	0.15%	0.16%	0.01%	0.00%	0.00%
F	—[(b)]	—	—	—	—
Fe_2O_3	5.32%	10.76%	6.20%	5.63%	5.39%
K_2O	0.38%	0.37%	0.39%	0.40%	0.38%
La_2O_3	0.05%	0.06%	0.04%	0.04%	0.06%
Li_2O	**1.36%**	**1.00%**	**1.00%**	**2.06%**	**1.35%**
MnO	2.37%	2.59%	4.21%	4.01%	2.39%
MoO_3	0.47%	0.54%	0.03%	—	—
Na_2O	10.86%	14.25%	12.10%	10.38%	10.83%
NiO	0.36%	0.65%	0.65%	0.60%	0.18%
P_2O_5	0.76%	0.72%	0.03%	0.04%	0.04%
PbO	0.45%	0.49%	—	—	—
Pr_2O_3	0.11%	0.10%	0.12%	0.09%	0.12%
Rb_2O	0.03%	0.04%	0.05%	0.04%	0.04%
Rh_2O_3	0.06%	0.06%	0.07%	0.05%	0.04%
RuO_2	0.06%	0.06%	0.07%	0.05%	0.02%
SO_3	0.31%	0.45%	0.08%	0.08%	0.08%
Sb_2O_3	0.21%	0.22%	0.21%	0.21%	0.20%
SiO_2	40.72%	38.84%	41.24%	41.50%	41.15%
SnO_2	0.12%	0.14%	0.14%	0.13%	0.12%
SrO	6.20%	3.22%	7.00%	2.73%	6.18%
ThO_2	0.85%	0.97%	0.99%	0.92%	3.00%
UO_3	2.79%	1.52%	1.55%	1.93%	1.36%
WO_3	0.06%	0.07%	0.07%	0.06%	0.06%
Y_2O_3	0.05%	0.06%	0.06%	0.06%	0.05%
ZnO	0.46%	1.16%	1.57%	0.50%	1.37%
ZrO_2	2.15%	6.37%	2.51%	5.84%	4.09%
TOTAL	99.95%	99.80%	99.90%	99.79%	99.87%

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

Table 4.1 Compositional Analysis (wt%) of HLW Phase 2 Matrix Glasses by XRF (continued).

Oxides	HLW07-36	HLW07-37	HLW07-38	HLW07-39	HLW07-40
Al_2O_3	9.83%	5.38%	5.84%	6.22%	5.79%
B_2O_3	**11.00%**[(a)]	**8.00%**	**11.00%**	**11.00%**	**8.00%**
CaO	0.18%	0.17%	0.18%	0.18%	0.19%
CdO	—[(b)]	0.50%	0.48%	0.50%	0.52%
Ce_2O_3	0.24%	0.23%	0.24%	0.23%	0.23%
Cl	0.16%	0.12%	0.16%	0.15%	0.17%
CoO	—	0.16%	0.14%	0.14%	0.14%
Cr_2O_3	0.20%	0.19%	0.46%	0.50%	0.50%
Cs_2O	0.15%	0.13%	0.15%	0.15%	0.16%
CuO	0.01%	0.16%	0.15%	0.15%	0.17%
F	—	—	—	—	—
Fe_2O_3	5.93%	10.32%	6.12%	5.82%	10.17%
K_2O	0.43%	0.38%	0.41%	0.43%	0.41%
La_2O_3	0.06%	0.05%	0.05%	0.03%	0.04%
Li_2O	**1.00%**	**3.50%**	**1.00%**	**1.00%**	**1.00%**
MnO	2.65%	4.20%	4.01%	2.59%	2.63%
MoO_3	0.03%	0.53%	0.50%	—	0.03%
Na_2O	13.38%	13.61%	10.44%	13.02%	9.55%
NiO	0.21%	0.20%	0.20%	0.19%	0.20%
P_2O_5	0.03%	0.73%	0.71%	0.03%	—
PbO	—	0.49%	0.47%	0.49%	0.49%
Pr_2O_3	0.13%	0.11%	0.09%	0.10%	0.11%
Rb_2O	0.04%	0.04%	0.04%	0.05%	0.04%
Rh_2O_3	0.08%	0.04%	0.05%	0.04%	0.07%
RuO_2	0.07%	0.05%	0.04%	0.04%	0.07%
SO_3	0.08%	0.39%	0.27%	0.07%	0.13%
Sb_2O_3	0.25%	0.22%	0.20%	0.21%	0.20%
SiO_2	39.33%	39.10%	41.46%	44.50%	41.80%
SnO_2	0.14%	0.14%	0.13%	0.14%	0.15%
SrO	6.98%	2.55%	2.40%	2.47%	7.08%
ThO_2	1.01%	3.51%	3.28%	0.96%	3.48%
UO_3	3.14%	1.59%	1.50%	1.52%	2.09%
WO_3	0.07%	0.06%	0.07%	0.07%	0.08%
Y_2O_3	0.06%	0.06%	0.06%	0.06%	0.06%
ZnO	0.52%	0.55%	1.47%	0.52%	1.55%
ZrO_2	2.52%	2.47%	6.04%	6.26%	2.58%
TOTAL	99.91%	99.93%	99.81%	99.82%	99.87%

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

Table 4.2. PCT Release Data (Leachate Concentration in ppm and Normalized Release in g/l) for the HLW Phase 2 Matrix 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
HLW07-01	10.43	3.98	35.48	0.365	0.475	0.424	10.21
HLW07-02	14.29	10.73	27.78	0.503	0.624	0.416	10.11
HLW07-03	14.91	10.74	31.02	0.550	0.623	0.460	10.35
HLW07-04	27.13	20.58	2.10	0.624	0.738	0.071	9.61
HLW07-05	32.39	31.35	124.50	2.103	1.421	1.435	11.14
HLW07-06	4.64	0.00	38.67	0.249	—[a]	0.416	10.38
HLW07-07	113.00	0.00	635.90	6.065	—	4.768	11.92
HLW07-08	11.98	0.20	122.00	0.643	—	0.913	11.20
HLW07-09	6.79	14.83	44.39	0.365	0.709	0.695	11.08
HLW07-10	29.43	0.17	61.32	0.799	—	0.874	9.81
HLW07-11	18.19	18.95	187.00	0.976	0.906	1.481	11.53
HLW07-12	23.69	20.67	214.80	1.271	1.008	1.617	11.65
HLW07-13	11.73	1.33	119.30	0.630	0.363	0.893	11.32
HLW07-14	3.58	8.69	14.74	0.192	0.437	0.331	10.54
HLW07-15	22.27	0.25	208.00	1.195	—	1.557	11.53
HLW07-16	141.50	50.34	324.40	3.939	2.813	2.429	11.67
HLW07-17	234.90	90.10	457.60	5.819	4.561	3.426	11.67
HLW07-18	207.20	85.70	429.50	5.133	4.100	3.216	11.75
HLW07-19	29.90	31.54	233.50	1.465	1.613	2.090	11.81
HLW07-20	17.55	12.10	6.86	0.435	0.579	0.154	9.65
HLW07-21	5.11	0.27	36.01	0.274	—	0.428	10.39
HLW07-22	4.81	0.32	41.33	0.255	—	0.449	10.61
HLW07-23	17.58	4.49	18.88	0.435	0.531	0.384	9.53
HLW07-24	46.36	0.20	89.35	1.148	—	0.747	9.82
HLW07-25	6.84	2.49	36.03	0.367	0.537	0.424	10.14
HLW07-26	7.39	8.47	23.47	0.298	0.527	0.316	10.28
HLW07-27	12.91	7.67	28.62	0.378	0.472	0.386	10.25
HLW07-28	11.50	7.51	61.25	0.463	0.462	0.590	10.74
HLW07-29	22.13	3.10	44.50	0.648	0.667	0.556	9.93
HLW07-30	11.44	2.53	47.82	0.461	0.545	0.511	10.16
HLW07-31	10.51	2.44	23.44	0.308	0.387	0.316	9.75
HLW07-32	13.38	2.36	61.44	0.539	0.508	0.592	10.46
HLW07-33	6.21	1.49	34.67	0.250	0.321	0.381	10.24
HLW07-34	10.71	4.46	20.37	0.314	0.465	0.275	9.77
HLW07-35	8.69	2.49	25.00	0.292	0.398	0.337	9.95
HLW07-36	15.59	1.92	52.89	0.456	0.413	0.509	10.37
HLW07-37	35.00	19.68	116.50	1.409	1.210	1.137	11.15
HLW07-38	11.90	1.71	25.52	0.348	0.367	0.331	9.67
HLW07-39	13.23	2.25	45.05	0.387	0.485	0.446	10.16
HLW07-40	8.90	1.78	29.71	0.358	0.384	0.400	9.99

(a) — indicates empty data field (lithium is not present in these glasses).

Table 4.3. Normalized PCT Release Data and Standard Deviations for Replicates of the HLW Phase 2 Matrix Glasses.

Glass IDs of Replicate Pairs	Normalized PCT Releases (g/l)		
	Boron	**Lithium**	**Sodium**
HLW02-46	0.536	0.632	0.452
HLW07-02	0.503	0.624	0.416
% Relative Standard Deviation	**4.49%**	**0.90%**	**5.87%**
HLW03-41	0.498	0.560	0.464
HLW07-03	0.550	0.623	0.460
% Relative Standard Deviation	**7.02%**	**7.53%**	**0.61%**
HLW02-22	0.550	0.620	0.076
HLW07-04	0.624	0.738	0.071
% Relative Standard Deviation	**8.91%**	**12.29%**	**4.81%**
HLW03-07	2.892	1.874	2.088
HLW07-05	2.103	1.421	1.435
% Relative Standard Deviation	**22.34%**	**19.44%**	**26.21%**
Pooled % Relative Standard Deviation	**12.73%**	**12.11%**	**13.65%**

Table 4.4. Comparison of Pooled Percent Relative Standard Deviations of PCT Releases Obtained for the Replicate Pairs from Different Test Phases.

Test Phase	Boron	Lithium	Sodium
Initial and Augmentation Matrices from Phase 1 [1] (9 Replicate Pairs)	34.60	10.84	9.34
Spinel Matrix from Phase 1 [2] (2 Replicate Pairs)	15.10	18.97	7.01
Phase 2 Test Matrix (4 Replicate Pairs)	12.73	12.11	13.65

Table 4.5 Normalized PCT Results of the Reference Glass (DWPF-EA) from All Test Sets and Associated Standard Deviations.

Test Name	HLW07-Glasses Tested	PCT Results (Normalized Releases in g/l and Leachate pH)				
		Boron	Lithium	Sodium	Silicon	pH
HR7N	-07, -12, -13,-16, -32	19.00	9.83	12.58	3.75	11.78
HR7O	-10, -11, -14, -15, -30	19.55	9.47	12.83	3.88	11.84
HR7Q	-18, -26, -37, -39	18.43	9.24	12.48	3.68	11.83
HR7R	-01, -08, -20, -21, -22	18.48	9.24	12.27	3.53	11.85
HR7S	--19, -24, -25, -33, -36	18.69	9.48	13.02	3.69	11.86
HR7T	-09, -28, -34, -38, -40	20.00	10.39	14.33	3.85	11.87
HR7U	-05, -06, -23, -31, -35	20.69	10.03	13.78	4.00	11.87
HR7V	-03, -27, -29	19.45	9.72	13.40	4.04	11.86
HA7L	-02 -04, -17	19.60	10.02	12.61	4.04	11.86
Mean and Standard Deviation		19.322 ± 0.750	9.712 ± 0.392	13.033 ± 0.679	3.828 ± 0.180	11.85 ± 0.03
% Relative Standard Deviation		3.88	4.03	5.21	4.71	0.24
Reference Glass DWPF-EA [13]		16.695 ± 1.222	9.565 ± 0.735	13.346 ± 0.902	3.922 ± 0.376	11.85 ± 0.10

Table 4.6. Measured and Fitted Viscosity Data for Selected HLW Phase 1 Matrix Glasses.

Glass ID	Measured Viscosity		Fitted Viscosity	
	Temperature (°C)	Viscosity (P)	Temperature (°C)	Viscosity (P)
HLW05-15	973	2992.30	1000	1852.59
	1072	607.76	1050	841.17
	1170	185.68	1100	422.08
	1269	69.68	1150	229.91
HLW05-20	965	732.91	1000	433.99
	1061	196.96	1050	226.53
	1162	72.86	1100	129.58
	1259	33.35	1150	79.78
HLW05-21	967	104.4	1000	67.07
	1067	30.90	1050	37.20
	1166	12.57	1100	22.32
	1265	6.14	1150	14.27
HLW05-22	968	1616.10	1000	1016.54
	1066	434.28	1050	532.57
	1163	155.59	1100	298.66
	1260	67.15	1150	177.46
HLW05-27	965	164.21	1000	109.61
	1064	56.64	1050	64.65
	1162	23.57	1100	40.20
	1260	11.60	1150	26.15
HLW06-02	967	202.89	1000	134.50
	1066	65.65	1050	76.22
	1163	25.72	1100	46.04
	1262	12.61	1150	29.34
HLW06-04	1015	—[a]	1000	—[b]
	1066	—[a]	1050	—[b]
	1166	30.79	1100	—[b]
	1268	13.82	1150	—[b]
HLW06-22	962	87.41	1000	56.26
	1060	31.33	1050	34.14
	1159	14.30	1100	22.27
	1264	7.85	1150	15.39
HLW06-32	960	41.34	1000	26.84
	1056	15.66	1050	16.54
	1151	7.27	1100	10.75
	1246	3.85	1150	7.31
HLW06-34	961	143.12	1000	77.67
	1059	35.47	1050	39.55
	1158	12.49	1100	22.21
	1256	5.69	1150	13.48

[a] Non-Newtonian behavior observed at T ≤ 1066°C; no data were measured for these temperatures.
[b] Fitting to the Vogel-Fulcher equation was not performed.

Table 4.7. Measured and Fitted Electrical Conductivity Data for Selected HLW Phase 1 Matrix Glasses.

Glass ID	Measured Electrical Conductivity		Fitted Electrical Conductivity	
	Temperature (°C)	Conductivity (S/cm)	Temperature (°C)	Conductivity (S/cm)
HLW05-15	973	2992.3	1000	0.208
	1072	607.76	1050	0.253
	1170	185.68	1100	0.299
	1269	69.68	1150	0.344
HLW05-20	965	732.91	1000	0.263
	1061	196.96	1050	0.326
	1162	72.86	1100	0.387
	1259	33.35	1150	0.445
HLW05-21	967	104.4	1000	0.312
	1067	30.90	1050	0.389
	1166	12.57	1100	0.465
	1265	6.14	1150	0.537
HLW05-22	968	1616.10	1000	0.110
	1066	434.28	1050	0.138
	1163	155.59	1100	0.169
	1260	67.15	1150	0.203
HLW05-27	965	164.21	1000	0.309
	1064	56.64	1050	0.380
	1162	23.57	1100	0.459
	1260	11.60	1150	0.548
HLW06-02	939	0.244	1000	0.312
	1040	0.363	1050	0.379
	1136	0.499	1100	0.453
	1231	0.697	1150	0.535
HLW06-04	932	0.268	1000	0.341
	1033	0.385	1050	0.403
	1132	0.491	1100	0.470
	1228	0.687	1150	0.542
HLW06-22	933	0.163	1000	0.225
	1033	0.259	1050	0.284
	1131	0.379	1100	0.352
	1226	0.592	1150	0.430
HLW06-32	954	0.277	1000	0.339
	1043	0.398	1050	0.414
	1133	0.557	1100	0.493
	1223	0.699	1150	0.577
HLW06-34	934	0.214	1000	0.289
	1033	0.333	1050	0.355
	1130	0.475	1100	0.430
	1220	0.650	1150	0.514

Table 4.8. Measured and Fitted Viscosity Data for HLW Phase 2 Matrix Glasses.

Glass ID	Measured Viscosity		Fitted Viscosity	
	Temperature (°C)	Viscosity (P)	Temperature (°C)	Viscosity (P)
HLW07-01	975	789.61	1000	526.12
	1071	199.52	1050	254.90
	1166	67.03	1100	137.60
	1262	31.50	1150	80.92
HLW07-02	974	439.11	1000	325.30
	1074	150.59	1050	190.52
	1173	62.41	1100	117.41
	1274	29.67	1150	75.62
HLW07-03	956	359.53	1000	174.20
	1056	80.62	1050	91.60
	1158	37.50	1100	54.78
	1260	16.94	1150	35.97
HLW07-04	948	888.65	1000	473.61
	1049	281.79	1050	276.93
	1151	109.69	1100	171.54
	1253	52.33	1150	111.59
HLW07-05	979	92.23	1000	68.36
	1067	31.76	1050	36.25
	1157	12.18	1100	21.57
	1247	7.51	1150	14.00
HLW07-06	977	1679.69	1000	1054.55
	1065	336.71	1050	430.10
	1155	96.44	1100	199.40
	1245	35.88	1150	102.42
HLW07-07	971	107.57	1000	73.81
	1066	36.07	1050	42.18
	1160	16.69	1100	26.46
	1255	9.19	1150	17.84
HLW07-08	Highly non-Newtonian behavior observed at all measurement temperatures			
HLW07-09	972[a]	121.42	1000	79.59
	1064	35.05	1050	41.06
	1158	13.48	1100	23.45
	1252	6.56	1150	14.51
HLW07-10	974	285.30	1000	185.45
	1067	73.75	1050	89.98
	1162	25.67	1100	49.15
	1257	12.42	1150	29.43

[a] Non-Newtonian behavior noticeable at 972°C.

Table 4.8. Measured and Fitted Viscosity Data for HLW Phase 2 Matrix Glasses (continued).

Glass ID	Measured Viscosity		Fitted Viscosity	
	Temperature (°C)	Viscosity (P)	Temperature (°C)	Viscosity (P)
HLW07-11	956	119.30	1000	68.78
	1056	37.73	1050	40.50
	1156	17.02	1100	25.77
	1256	8.84	1150	17.45
HLW07-12	975[(a)]	162.44	1000	118.72
	1067[(a)]	56.58	1050	64.88
	1161	19.44	1100	37.66
	1255	9.67	1150	23.03
HLW07-13	1014	1063.25	1000	1317.49
	1062	531.96	1050	630.58
	1160	170.87	1100	331.32
	1259[(b)]	66.85	1150	187.94
HLW07-14	Highly non-Newtonian behavior observed at all measurement temperatures			
HLW07-15	972	351.34	1000	214.05
	1066	79.23	1050	97.94
	1162	24.35	1100	50.19
	1258	10.27	1150	28.15
HLW07-16	951	55.89	1000	31.91
	1056	17.99	1050	19.18
	1160	7.49	1100	12.15
	1263	3.60	1150	8.04
HLW07-17	983	45.10	1000	38.45
	1074	20.32	1050	25.04
	1170	10.45	1100	16.90
	1264	5.65	1150	11.76
HLW07-18	965	47.64	1000	34.84
	1059	22.06	1050	22.59
	1153	9.77	1100	15.19
	1247	5.74	1150	10.55
HLW07-19	979	57.90	1000	43.35
	1068	19.61	1050	23.49
	1159	8.19	1100	14.00
	1251	4.41	1150	9.00
HLW07-20	966	685.48	1000	419.62
	1062	195.47	1050	225.79
	1158	80.72	1100	133.45
	1254	39.36	1150	84.94

[(a)] Crystallization suspected for measurements at $T \leq 1067$°C.
[(b)] Measurement at 1259°C is of poor quality.

Table 4.8. Measured and Fitted Viscosity Data for HLW Phase 2 Matrix Glasses (continued).

Glass ID	Measured Viscosity		Fitted Viscosity	
	Temperature (°C)	Viscosity (P)	Temperature (°C)	Viscosity (P)
HLW07-21	1016	2575.47	1000	3701.56
	1065	1051.18	1050	1336.15
	1165	224.06	1100	571.58
	1265	76.84	1150	278.64
HLW07-22	951	2718.96	1000	1164.81
	1053	517.46	1050	543.31
	1155	142.90	1100	275.83
	1256	50.16	1150	150.39
HLW07-23	966	1012.38	1000	592.17
	1062	261.17	1050	295.34
	1160	85.00	1100	162.68
	1258	39.65	1150	97.03
HLW07-24	972	1252.76	1000	789.36
	1067	308.82	1050	379.61
	1164	101.86	1100	203.31
	1261	45.25	1150	118.61
HLW07-25	1020[a]	1454.75	1000	2011.77
	1067	669.47	1050	891.46
	1165	229.41	1100	454.54
	1263	93.67	1150	257.91
HLW07-26	961	1004.53	1000	574.78
	1059	274.78	1050	308.61
	1157	106.99	1100	179.83
	1255	48.76	1150	112.01
HLW07-27	980	282.33	1000	215.19
	1068	95.47	1050	113.85
	1158	35.69	1100	65.22
	1248	17.96	1150	39.90
HLW07-28	972	1060.19	1000	644.14
	1063	250.59	1050	293.27
	1156	77.79	1100	150.71
	1249	34.29	1150	85.17
HLW07-29	965	396.92	1000	231.35
	1061	106.47	1050	119.26
	1159	38.29	1100	68.30
	1257	19.02	1150	42.46
HLW07-30	966	1247.91	1000	737.67
	1061	327.15	1050	369.28
	1156	109.12	1100	201.78
	1251	48.47	1150	118.48

[a] Crystallization suspected.

Table 4.8. Measured and Fitted Viscosity Data for HLW Phase 2 Matrix Glasses (continued).

Glass ID	Measured Viscosity		Fitted Viscosity	
	Temperature (°C)	Viscosity (P)	Temperature (°C)	Viscosity (P)
HLW07-31	975	1295.89	1000	821.69
	1066	292.47	1050	376.29
	1159	99.38	1100	192.97
	1252	41.41	1150	108.31
HLW07-32	952	683.02	1000	327.76
	1054	162.34	1050	167.58
	1156	51.14	1100	93.08
	1258	21.82	1150	55.36
HLW07-33	974	1187.56	1000	741.65
	1062	284.76	1050	336.35
	1152	98.44	1100	173.66
	1242	42.40	1150	99.10
HLW07-34	980	1604.68	1000	1056.33
	1068	322.18	1050	435.69
	1158	101.75	1100	208.29
	1248	42.20	1150	111.55
HLW07-35	972	1396.56	1000	821.22
	1063	303.68	1050	366.42
	1156	98.02	1100	187.03
	1249	43.44	1150	105.87
HLW07-36	964	476.70	1000	282.37
	1059	135.80	1050	150.43
	1156	51.80	1100	87.68
	1253	25.02	1150	54.92
HLW07-37	970	104.93	1000	74.11
	1066	37.93	1050	44.17
	1160	17.51	1100	28.08
	1256	9.26	1150	18.83
HLW07-38	969	1151.04	1000	680.47
	1062	262.90	1050	317.95
	1157	81.89	1100	160.96
	1252	29.54	1150	87.22
HLW07-39	976	1502.00	1000	911.71
	1070	277.84	1050	376.95
	1163	86.34	1100	183.00
	1257	37.01	1150	100.21
HLW07-40	977	256.23	1000	180.11
	1066	76.59	1050	93.07
	1157	33.92	1100	54.22
	1248	16.83	1150	34.57

Table 4.9. Measured and Fitted Electrical Conductivity Data for HLW Phase 2 Matrix Glasses.

Glass ID	Measured Electrical Conductivity		Fitted Electrical Conductivity	
	Temperature (°C)	Conductivity (S/cm)	Temperature (°C)	Conductivity (S/cm)
HLW07-01	933	0.079	1000	0.122
	1035	0.150	1050	0.156
	1132	0.200	1100	0.189
	1231	0.276	1150	0.221
HLW07-02	983	0.113	1000	0.125
	1080	0.186	1050	0.161
	1177	0.264	1100	0.200
	1274	0.360	1150	0.243
HLW07-03	950	0.133	1000	0.178
	1048	0.227	1050	0.228
	1145	0.331	1100	0.282
	1239	0.442	1150	0.338
HLW07-04	973	0.149	1000	0.168
	1072	0.223	1050	0.207
	1170	0.310	1100	0.248
	1269	0.402	1150	0.292
HLW07-05	965	0.308	1000	0.374
	1062	0.496	1050	0.473
	1160	0.703	1100	0.576
	1253	0.894	1150	0.680
HLW07-06	960	0.070	1000	0.091
	1057	0.126	1050	0.121
	1154	0.192	1100	0.154
	1249	0.269	1150	0.190
HLW07-07	962	0.178	1000	0.218
	1058	0.285	1050	0.277
	1155	0.419	1100	0.340
	1249	0.552	1150	0.409
HLW07-08	951	0.157	1000	0.203
	1049	0.245	1050	0.248
	1144	0.341	1100	0.290
	1239	0.384	1150	0.331
HLW07-09	960	0.167	1000	0.214
	1058	0.294	1050	0.281
	1153	0.446	1100	0.357
	1252	0.645	1150	0.443
HLW07-10	956	0.039	1000	0.052
	1053	0.072	1050	0.071
	1149	0.122	1100	0.094
	1243	0.191	1150	0.123

Table 4.9. Measured and Fitted Electrical Conductivity Data for HLW Phase 2 Matrix Glasses (continued).

Glass ID	Measured Electrical Conductivity		Fitted Electrical Conductivity	
	Temperature (°C)	Conductivity (S/cm)	Temperature (°C)	Conductivity (S/cm)
HLW07-11	950	0.289	1000	0.368
	1048	0.432	1050	0.446
	1145	0.609	1100	0.519
	1240	0.683	1150	0.588
HLW07-12	960	0.324	1000	0.400
	1057	0.523	1050	0.496
	1154	0.671	1100	0.594
	1249	0.901	1150	0.692
HLW07-13	958	0.181	1000	0.220
	1055	0.273	1050	0.275
	1150	0.423	1100	0.337
	1245	0.550	1150	0.407
HLW07-14	937	0.072	1000	0.105
	1033	0.133	1050	0.136
	1128	0.182	1100	0.173
	1219	0.295	1150	0.216
HLW07-15	948	0.175	1000	0.244
	1045	0.305	1050	0.317
	1141	0.469	1100	0.395
	1233	0.612	1150	0.477
HLW07-16	981	0.524	1000	0.571
	1076	0.780	1050	0.698
	1173	1.023	1100	0.835
	1270	1.376	1150	0.981
HLW07-17	979	0.424	1000	0.463
	1078	0.618	1050	0.560
	1177	0.816	1100	0.660
	1277	1.035	1150	0.763
HLW07-18	954	0.335	1000	0.401
	1052	0.492	1050	0.479
	1149	0.634	1100	0.564
	1245	0.867	1150	0.657
HLW07-19	964	0.347	1000	0.418
	1059	0.549	1050	0.525
	1154	0.772	1100	0.642
	1251	1.046	1150	0.767
HLW07-20	946	0.082	1000	0.111
	1046	0.141	1050	0.142
	1142	0.211	1100	0.179
	1237	0.312	1150	0.221

Table 4.9. Measured and Fitted Electrical Conductivity Data for HLW Phase 2 Matrix Glasses (continued).

Glass ID	Measured Electrical Conductivity		Fitted Electrical Conductivity	
	Temperature (°C)	Conductivity (S/cm)	Temperature (°C)	Conductivity (S/cm)
HLW07-21	943	0.034	1000	0.050
	1043	0.064	1050	0.067
	1141	0.107	1100	0.088
	1239	0.167	1150	0.112
HLW07-22	941	0.038	1000	0.059
	1039	0.078	1050	0.080
	1135	0.116	1100	0.104
	1232	0.187	1150	0.132
HLW07-23	961	0.044	1000	0.056
	1058	0.076	1050	0.075
	1155	0.132	1100	0.098
	1250	0.191	1150	0.125
HLW07-24	911	0.140	1000	0.216
	1010	0.225	1050	0.264
	1105	0.323	1100	0.315
	1197	0.418	1150	0.368
HLW07-25	965	0.074	1000	0.086
	1063	0.112	1050	0.108
	1160	0.167	1100	0.133
	1259	0.239	1150	0.162
HLW07-26	962	0.095	1000	0.115
	1061	0.155	1050	0.147
	1160	0.231	1100	0.183
	1256	0.330	1150	0.224
HLW07-27	923	0.121	1000	0.178
	1020	0.185	1050	0.226
	1115	0.321	1100	0.282
	1210	0.425	1150	0.346
HLW07-28	959	0.062	1000	0.083
	1058	0.115	1050	0.113
	1154	0.193	1100	0.146
	1248	0.254	1150	0.182
HLW07-29	960	0.086	1000	0.103
	1057	0.129	1050	0.130
	1153	0.206	1100	0.161
	1247	0.274	1150	0.196
HLW07-30	946	0.076	1000	0.109
	1046	0.141	1050	0.142
	1140	0.202	1100	0.177
	1235	0.274	1150	0.212

Table 4.9. Measured and Fitted Electrical Conductivity Data for HLW Phase 2 Matrix Glasses (continued).

Glass ID	Measured Electrical Conductivity		Fitted Electrical Conductivity	
	Temperature (°C)	Conductivity (S/cm)	Temperature (°C)	Conductivity (S/cm)
HLW07-31	935	0.062	1000	0.093
	1031	0.109	1050	0.121
	1126	0.169	1100	0.150
	1218	0.227	1150	0.182
HLW07-32	961	0.093	1000	0.117
	1058	0.156	1050	0.148
	1154	0.236	1100	0.182
	1252	0.293	1150	0.220
HLW07-33	958	0.094	1000	0.119
	1054	0.156	1050	0.154
	1150	0.239	1100	0.194
	1246	0.339	1150	0.239
HLW07-34	933	0.079	1000	0.116
	1031	0.135	1050	0.151
	1118	0.208	1100	0.194
	1223	0.337	1150	0.244
HLW07-35	958	0.061	1000	0.081
	1055	0.113	1050	0.107
	1152	0.159	1100	0.135
	1249	0.238	1150	0.166
HLW07-36	959	0.128	1000	0.163
	1057	0.219	1050	0.209
	1152	0.315	1100	0.260
	1252	0.437	1150	0.315
HLW07-37	954	0.185	1000	0.232
	1052	0.288	1050	0.291
	1150	0.438	1100	0.356
	1244	0.579	1150	0.429
HLW07-38	957	0.075	1000	0.099
	1055	0.134	1050	0.130
	1150	0.205	1100	0.166
	1245	0.289	1150	0.205
HLW07-39	946	0.090	1000	0.120
	1046	0.147	1050	0.150
	1144	0.216	1100	0.183
	1242	0.284	1150	0.218
HLW07-40	953	0.221	1000	0.293
	1051	0.370	1050	0.369
	1147	0.527	1100	0.444
	1240	0.626	1150	0.517

Table 4.10. Viscosity and Electrical Conductivity Data and Standard Deviations for Replicates of the HLW Phase 2 Matrix Glasses.

Glass IDs of Replicate Pairs	Viscosity (P) at 1150ºC	Electrical Conductivity (S/cm) at 1150ºC
HLW02-46	52.16	0.232
HLW07-02	75.62	0.243
% Relative Standard Deviation	**25.96%**	**3.16%**
HLW03-41	37.79	0.300
HLW07-03	35.97	0.338
% Relative Standard Deviation	**3.50%**	**8.43%**
HLW02-22	102.69	0.226
HLW07-04	111.59	0.292
% Relative Standard Deviation	**5.87%**	**17.96%**
HLW03-07	13.16	0.685
HLW07-05	14.00	0.680
% Relative Standard Deviation	**4.35%**	**0.51%**
Pooled % Relative Standard Deviation	**13.60%**	**10.05%**

Table 4.11. Temperature and Volume %-Crystallinity Data for HLW Phase 2 Matrix Glasses.

Glass ID	Heat-Treatment Temperature (°C)										
	700	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**	**1150**	**1200**
HLW07-01	—[a]	—	**1.9**[b]	**1.4**	**1.0**	**0.9**	**0.5**	—	—	—	—
HLW07-02	—	—	**2.3**	**1.7**	**1.6**	**0.9**	**0.7**	—	—	—	—
HLW07-03	0.8	1.2	**1.2**	**1.0**	**0.6**	**0.4**	—	—	—	—	—
HLW07-04	—	25.0	**1.9**	**0.6**	**0.4**	**0.3**	—	—	—	—	—
HLW07-05	—	—	—	—	—	—	**3.5**	**3.1**	**3.3**	**2.0**	**0.5**
HLW07-06	—	—	—	—	**5.8**	**3.1**	**3.4**	**0.8**	**0.5**	—	—
HLW07-07	**15.7**	**4.4**	**1.0**	0.2	0.3	—	—	—	—	—	—
HLW07-08	—	—	—	9.3	—	—	—	**9.4**	**4.9**	**4.2**	**4.2**
HLW07-09	—	—	—	5.1	—	—	**4.9**	**3.2**	**1.2**	**1.7**	**1.1**
HLW07-10	—	—	**2.7**	**2.1**	**1.2**	**1.0**	—	**0.5**	—	—	—
HLW07-11	—	—	13.8	—	**2.2**	**1.4**	**1.2**	**0.7**	**0.3**	—	—
HLW07-12	—	—	24.9	—	—	**1.5**	**1.6**	**1.4**	**1.6**	**1.1**	**1.0**
HLW07-13	—	—	21.1	—	—	—	**3.2**	**3.6**	**3.1**	**2.1**	**3.1**
HLW07-14	—	—	**6.9**	—	—	—	**4.4**	**2.6**	**3.5**	**4.1**	**2.8**
HLW07-15	—	—	**22.2**		—	—	**14.3**	**7.5**	**4.7**	**0.6**	**0.9**
HLW07-16	—	—	—	4.8	**2.0**	**1.0**	**1.1**	**0.5**	**0.7**	—	—
HLW07-17	**5.8**	**4.3**	—	**0.7**	**0.3**	—	—	—	—	—	—
HLW07-18	0.6	**1.4**	**0.6**	**0.5**	0.4	—	—	—	—	—	—
HLW07-19	—	—	**13.1**	**11.8**		**2.5**	**2.5**	**0.7**	0.4	0.5	—
HLW07-20	—	—	**2.6**	**2.0**	**1.3**	**1.2**	**0.8**	**0.7**	—	—	—
HLW07-21	—	0.2	**0.8**	**0.7**	**0.1**	**0.2**	—	—	—	—	—
HLW07-22	—	—	13.0	—	—	—	**2.7**	**1.7**	**1.7**	**1.4**	**0.9**
HLW07-23	—	—	—	**5.6**	—	—	**5.4**	**4.9**	**3.0**	**3.8**	**2.4**
HLW07-24	—	—	**2.0**	—	**1.6**	**1.4**	**1.4**	**0.9**	—	—	—
HLW07-25	—	—	**4.3**	**4.0**	—		**2.7**	**3.3**	**1.6**	**1.2**	—
HLW07-26	—	**1.4**	0.9	**1.2**	**1.0**	**0.8**	**0.8**	—	—	—	—
HLW07-27	**1.1**	**1.2**	**1.1**	**0.9**	**0.5**	**0.4**	—	—	—	—	—
HLW07-28	—	**1.5**	**1.5**	**1.2**	**1.0**	**0.8**	—	—	—	—	—
HLW07-29	—	**3.2**	**2.6**	**2.3**	**1.8**	**1.2**	**0.8**	—	—	—	—
HLW07-30	—	—	**1.5**	**1.4**	**0.9**	**0.6**	**0.5**	—	—	—	—
HLW07-31	—	—	**1.5**	**1.2**	**1.0**	**0.8**	**0.6**	—	—	—	—
HLW07-32	—	—	**2.1**	**1.7**	**1.6**	**1.1**	**0.7**	—	—	—	—
HLW07-33	—	—	**2.3**	**2.0**	**1.7**	**1.3**	**1.0**	—	—	—	—
HLW07-34	—	—	**2.8**	**2.5**	**2.5**	**2.3**	**2.2**	**1.5**	**1.1**	—	—
HLW07-35	—	—	1.8	**1.9**	**1.8**	**1.7**	**1.2**	**0.8**	**0.4**	—	—
HLW07-36	—	0.2	0.3	0.2	—	0.2	—	—	—	—	—
HLW07-37	—	**2.1**	**1.5**	**1.0**	**0.5**	**0.3**	—	—	—	—	—
HLW07-38	—	**2.1**	—	**1.5**	**1.7**	**1.9**	**1.1**	—	**0.3**	—	—
HLW07-39	0.4	0.5	**0.8**	**0.5**	**0.5**	—	—	—	—	—	—
HLW07-40	—	**2.0**	**2.0**	**1.5**	**1.3**	**1.0**	**0.7**	—	—	—	—

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

Table 4.12. Regression Results[a], Estimated $T_{1\%}$, and the Major Crystalline Phase Near $T_{1\%}$ for Non-Spinel Matrix Glasses.

Glass ID	Type[b]	Intercept	Slope	$T_{1\%}$ (°C)	Crystalline Phase
HLW07-01	C	1066.17	-145.76	920.4	Spinel
HLW07-02	R	1072.25	-119.62	952.6	Spinel
HLW07-03	R	1015.00	-175.00	840.0	Spinel
HLW07-04	R	935.24	-75.30	859.9	Spinel
HLW07-05	R	1240.91	-56.82	1184.1	Spinel
HLW07-06	O	1093.78	-34.48	1059.3	Spinel
HLW07-07	O	793.64	-6.21	787.4	Spinel + Na (Al, Fe) Silicate
HLW07-08	O	1247.83	-21.64	1226.2	ThO_2 + ZrO_2
HLW07-09	O	1204.79	-43.30	1161.5	ZrO_2
HLW07-10	O	1065.25	-103.50	961.8	ThO_2 + Cr/Fe oxide
HLW07-11	O	1124.76	-107.55	1017.2	Spinel
HLW07-12	O	1464.50	-285.00	1179.5	ThO_2
HLW07-13	O	1309.04	-69.22	1239.8	ZrO_2
HLW07-14	O	1361.67	-76.95	1284.7	ZrO_2
HLW07-15	O	1186.81	-16.35	1170.5	ZrO_2
HLW07-16	O	1123.35	-116.37	1007.0	Spinel + ZrO_2
HLW07-17	O	892.47	-33.32	859.1	Spinel
HLW07-18	O	877.05	-92.47	784.6	ThO_2
HLW07-19	O	1034.77	-17.12	1017.7	ZrO_2
HLW07-20	O	1100.62	-122.52	978.1	Spinel
HLW07-21	O	947.97	-162.16	785.8	Strontium phosphate
HLW07-22	O	1289.58	-112.85	1176.7	ThO_2
HLW07-23	O	1398.22	-81.25	1317.0	Zircon
HLW07-24	O	1279.59	-232.59	1047.0	Spinel + ThO_2
HLW07-25	O	1283.49	-102.39	1181.1	ThO_2
HLW07-26	I	1264.71	-360.29	904.4	Spinel
HLW07-27	I	1044.43	-255.64	788.8	Spinel
HLW07-28	I	1150.00	-250.00	900.0	Spinel
HLW07-29	I	1081.58	-104.16	977.4	Spinel
HLW07-30	I	1065.70	-169.08	896.6	Spinel
HLW07-31	I	1129.92	-225.41	904.5	Spinel
HLW07-32	I	1105.37	-142.62	962.8	Spinel
HLW07-33	I	1150.82	-151.10	999.7	Spinel
HLW07-34	I	1305.68	-167.10	1138.6	ZrO_2 + Spinel
HLW07-35	I	1169.29	-149.46	1019.8	Spinel + ZrO_2 + ThO_2
HLW07-36	I	ND[c]	ND	ND	Spinel
HLW07-37	I	964.58	-106.09	858.5	Spinel
HLW07-38	I	1153.44	-159.38	994.1	Spinel
HLW07-39	I	1000.00	-250.00	750.0	Spinel
HLW07-40	I	1122.45	-174.67	947.8	Spinel

[a] Regression results are rounded to 2 decimal places for the intercept and slope, 1 decimal place for $T_{1\%}$ values.
[b] C = Center Point, R = Replicate, O = Outer Layer, I = Inner Layer.
[c] ND = Not determined (Regression was not performed).

Table 4.13. $T_{1\%}$ Data and Standard Deviations for Replicates of the Phase 2 Matrix Glasses.

Glass IDs of Replicate Pairs	Estimated $T_{1\%}$ (°C)	Standard Deviations (°C)
HLW02-46 HLW07-02	963.3 952.6	**7.57**
HLW03-41 HLW07-03	853.8 840.0	**9.76**
HLW02-22 HLW07-04	937.5 859.9	**54.87**
HLW03-07 HLW07-05	1213.2 1184.1	**20.58**
Standard Deviations Pooled Over 4 Replicate Pairs = **29.94**		

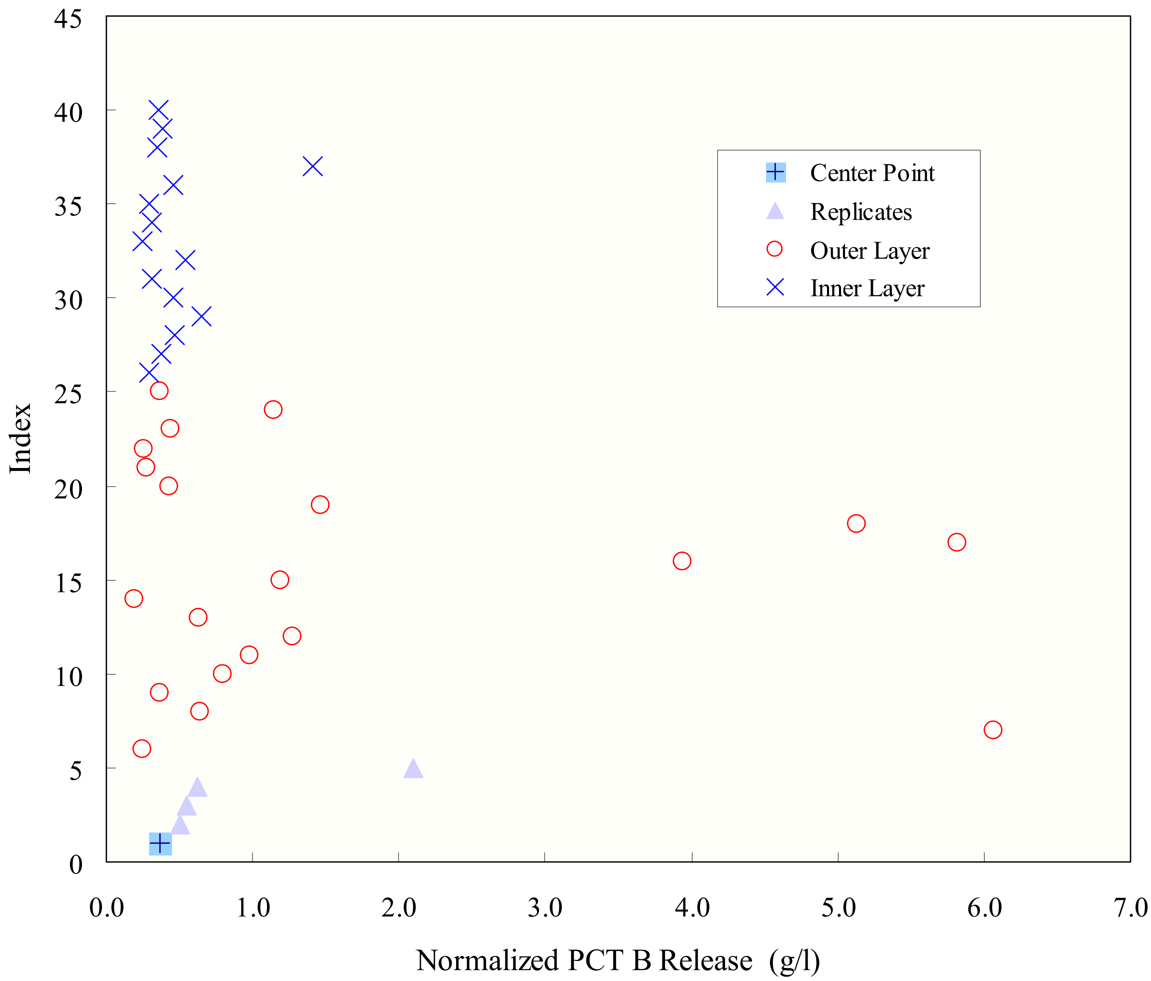


Figure 4.1. Distribution of normalized PCT boron release of the 40 HLW Phase 2 matrix glasses.

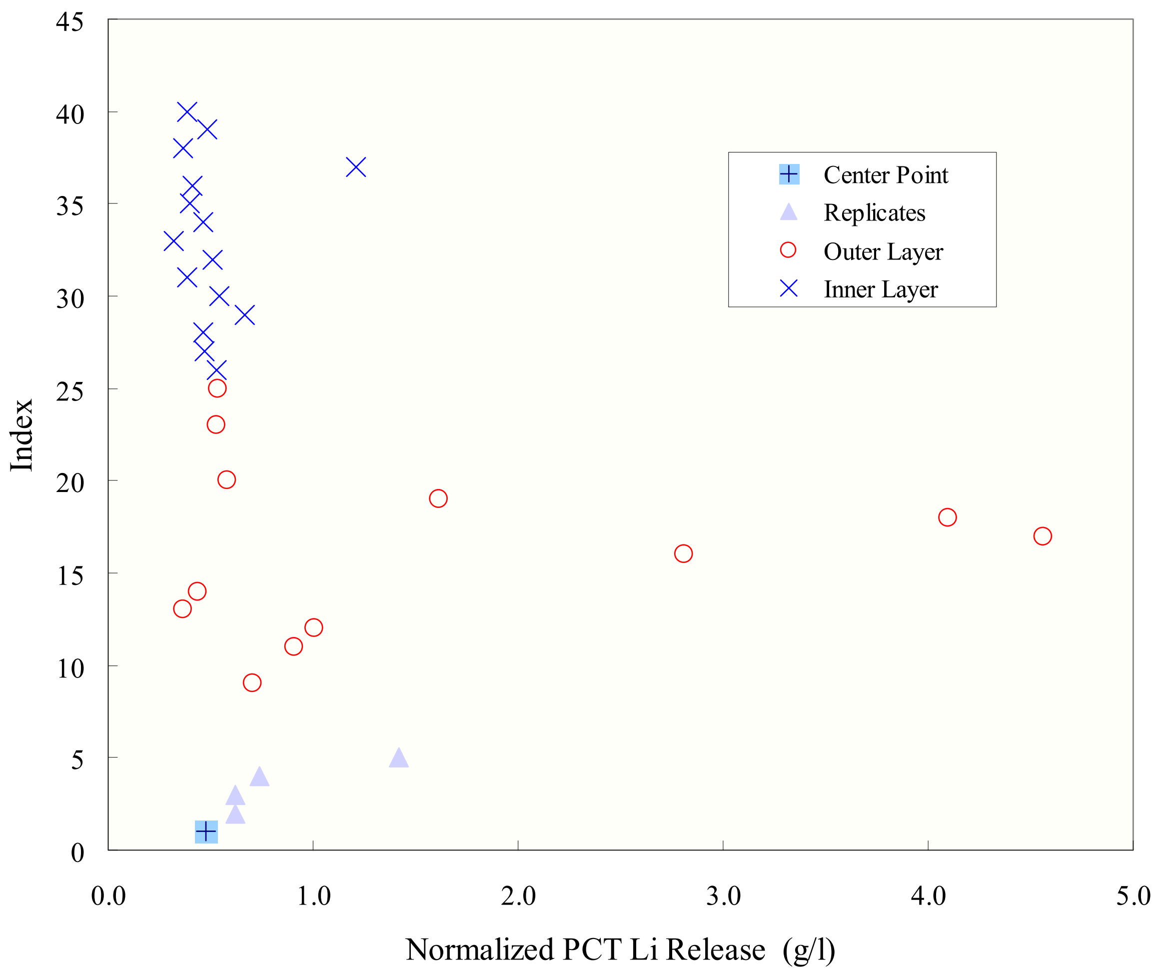


Figure 4.2. Distribution of normalized PCT lithium release of the 40 HLW Phase 2 matrix glasses.

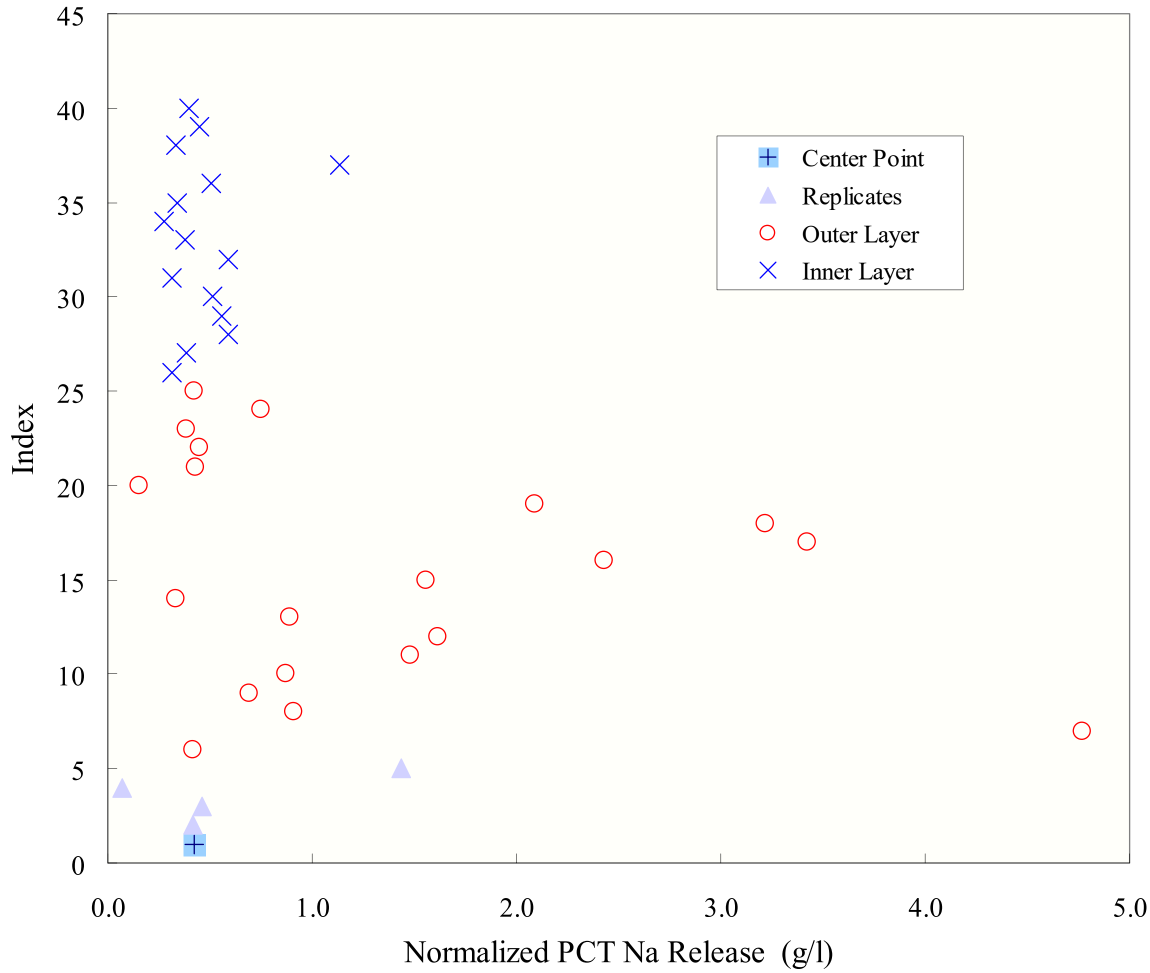


Figure 4.3. Distribution of normalized PCT sodium release of the 40 HLW Phase 2 matrix glasses.

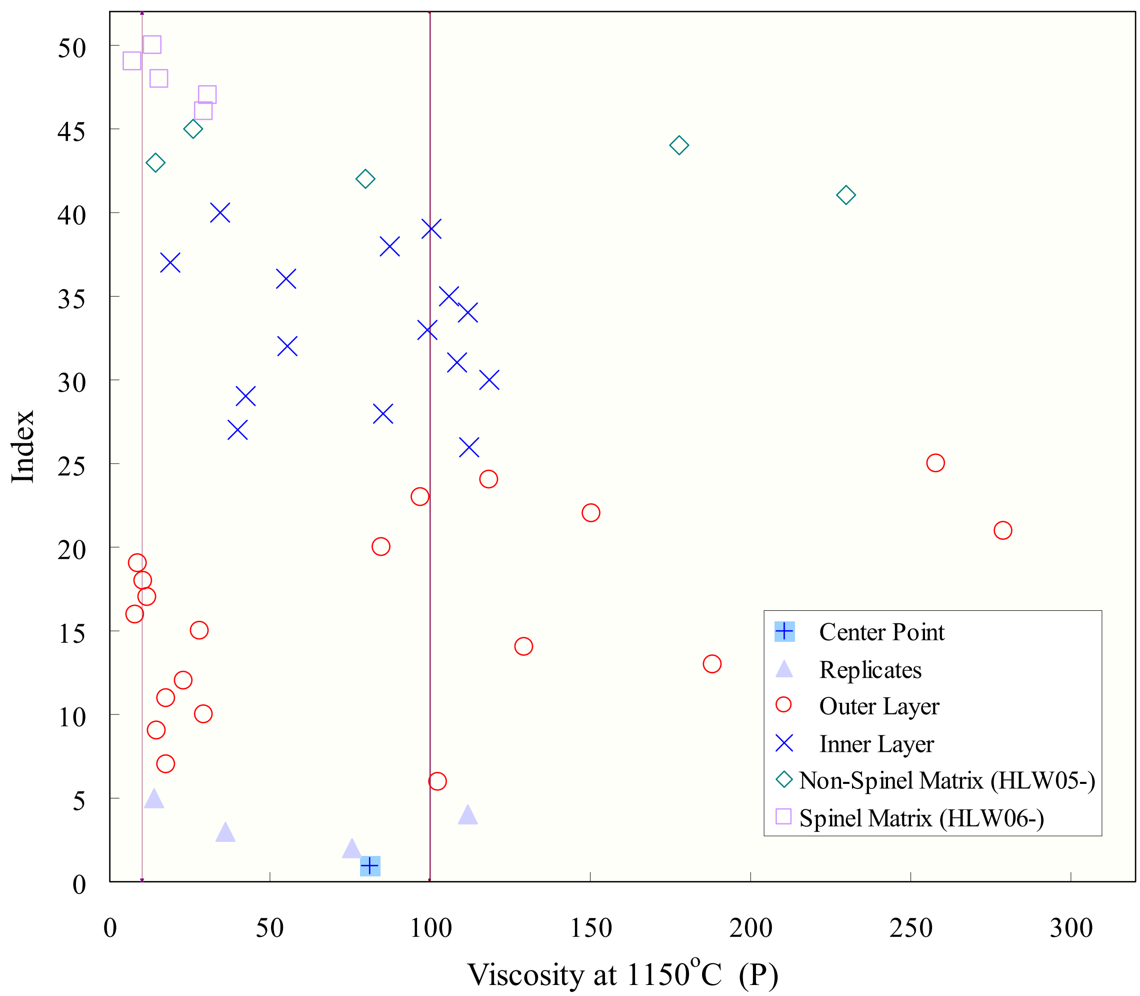


Figure 4.4. Distribution of viscosity at 1150ºC of the 10 HLW Phase 1 matrix glasses and 40 HLW Phase 2 matrix glasses. (The design lower and upper limits are marked with red lines. Measured viscosity at 1166ºC (Index = 47, Viscosity = 30.79 P) is used for glass HLW06-04.)

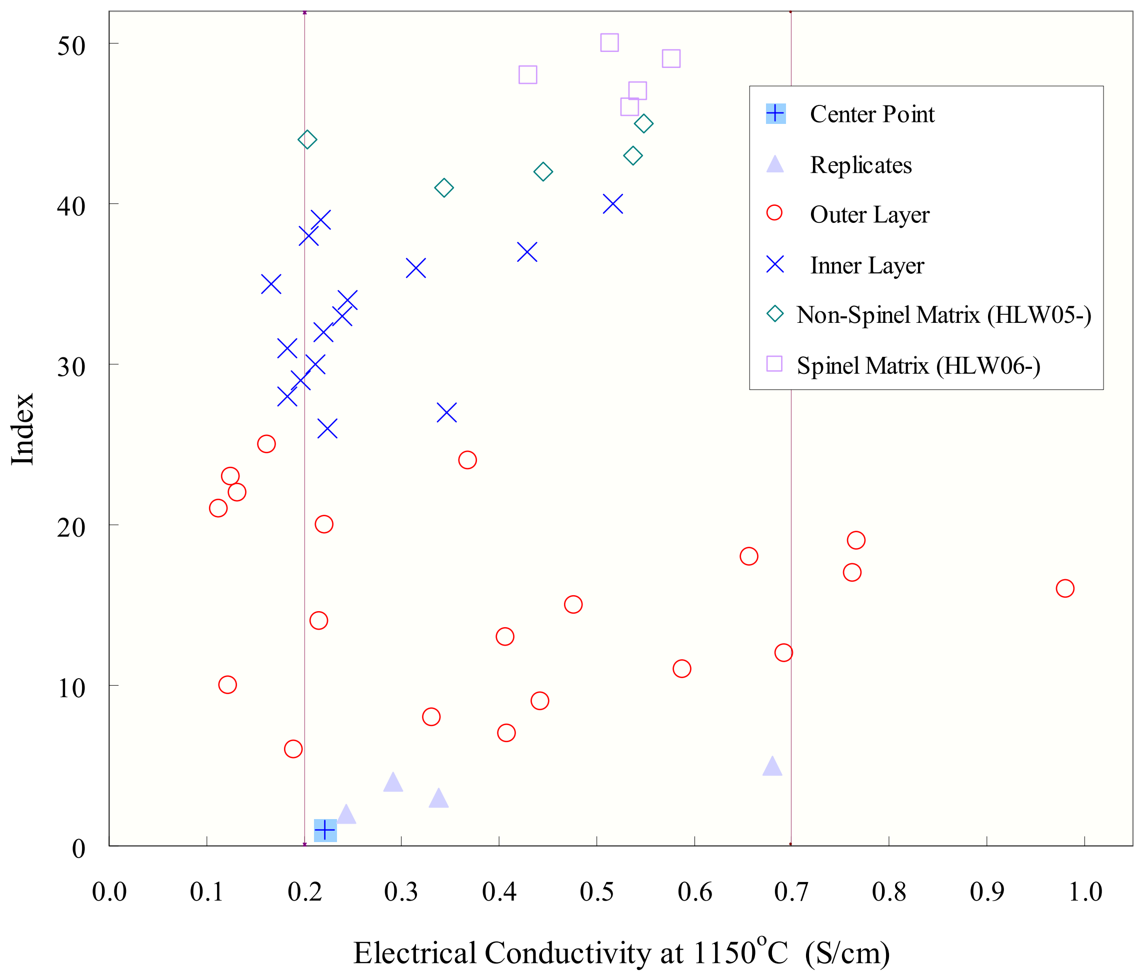


Figure 4.5. Distribution of electrical conductivity at 1150°C of the 10 HLW Phase 1 matrix glasses and 40 HLW Phase 2 matrix glasses. (The design lower and upper limits are marked with red lines.)

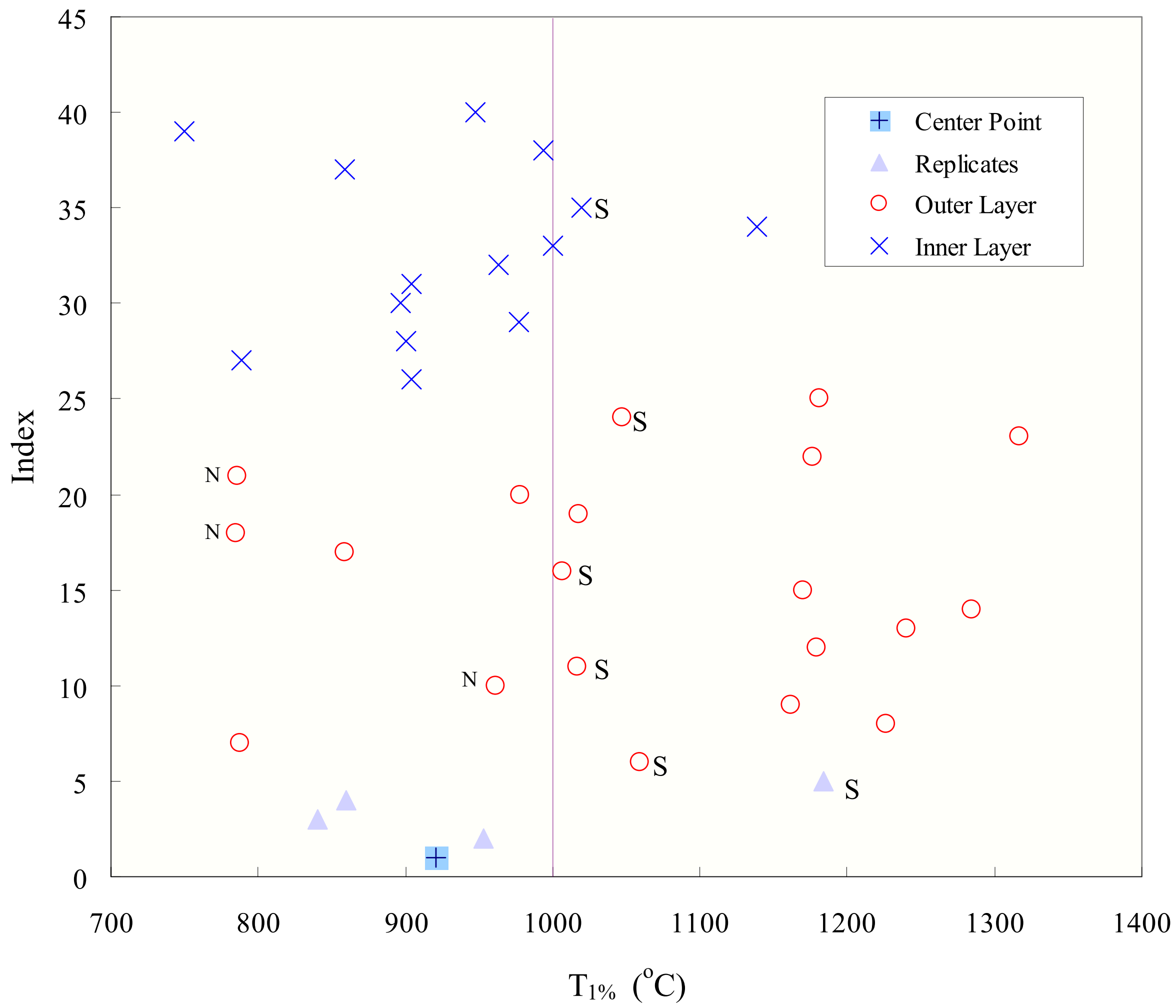
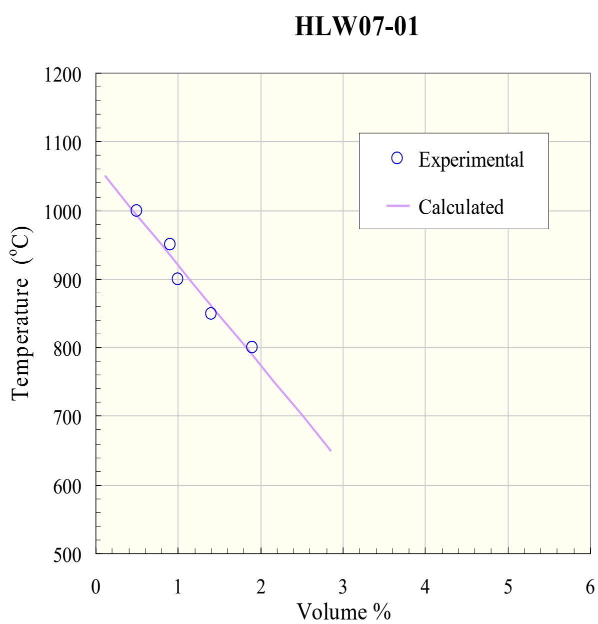
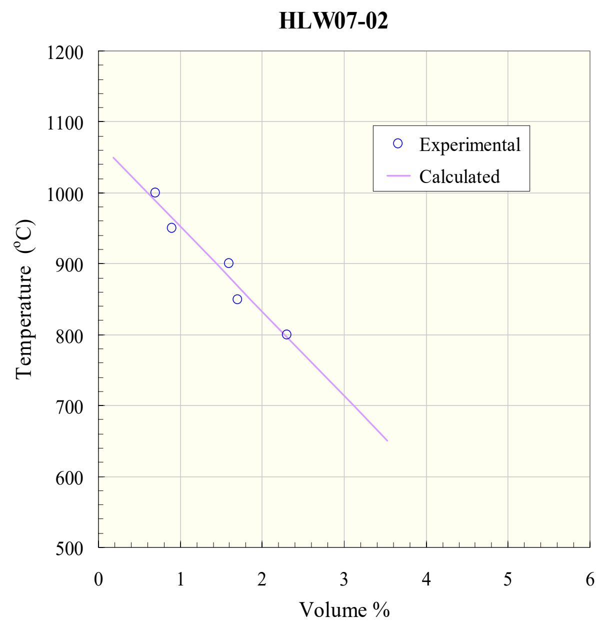


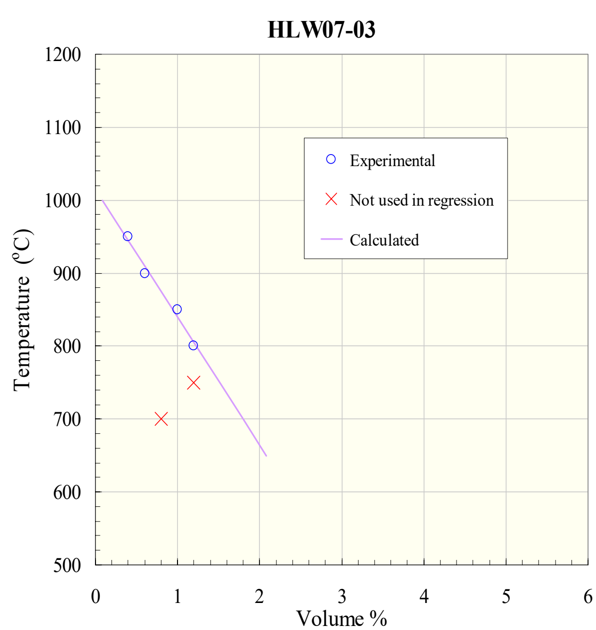
Figure 4.6. Distribution of estimated $T_{1\%}$ values of the 39 HLW Phase 2 matrix glasses. (The design upper limit is marked with a red line. The "S" symbol indicates glasses that crystallize spinel with $T_{1\%}$ > 1000°C and the "N" symbol indicates glasses that crystallize non-spinel phases with $T_{1\%}$ < 1000°C.)

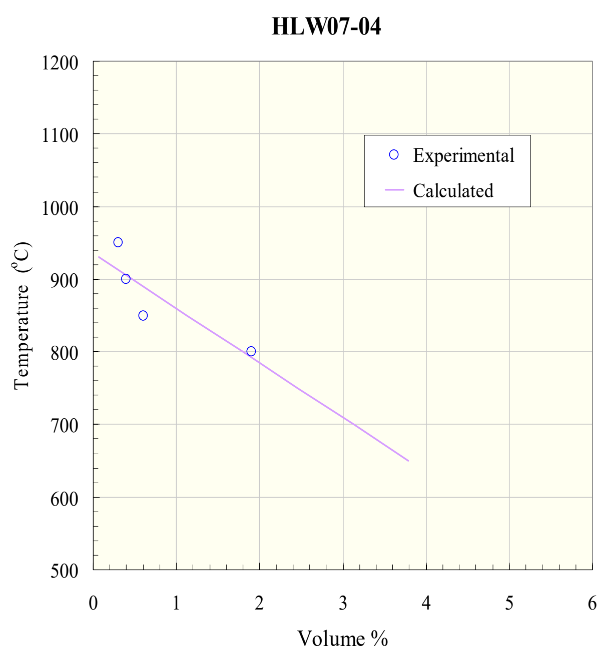
Appendix A
Plots of Crystallization Data and Regression

This appendix presents graphically heat treatment data collected for the WTP HLW Phase 2 modeling matrix glasses. For each of the 40 matrix 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 the glass HLW07-36, for which no regression was performed). To the extent possible, similar scales are used in the plots to facilitate comparison.

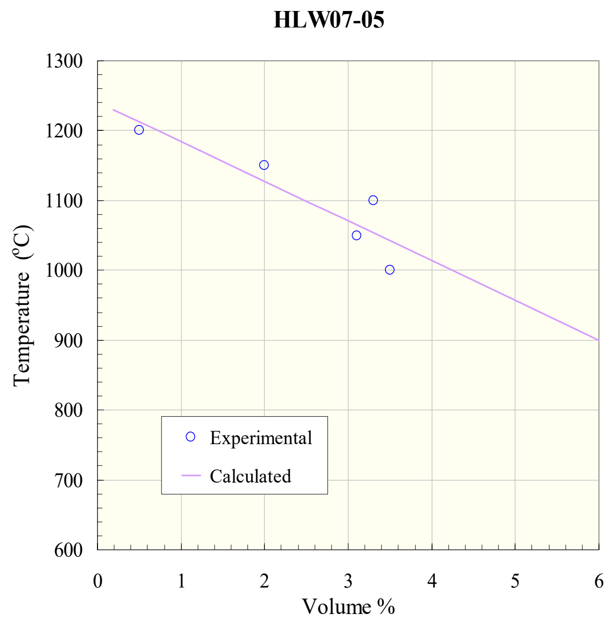


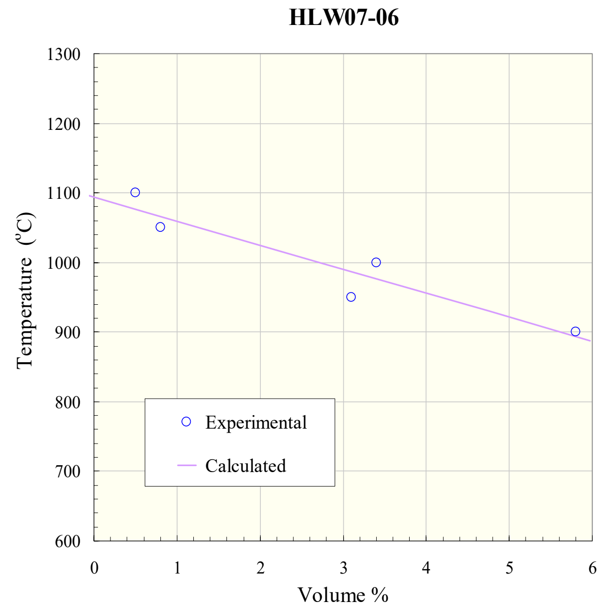


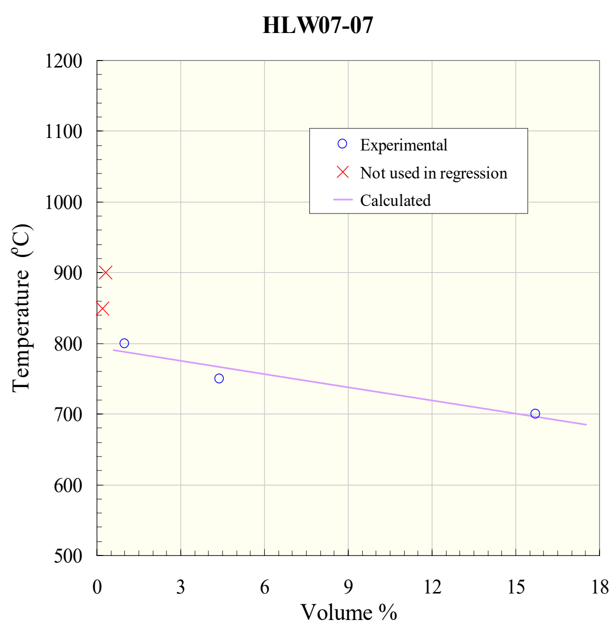


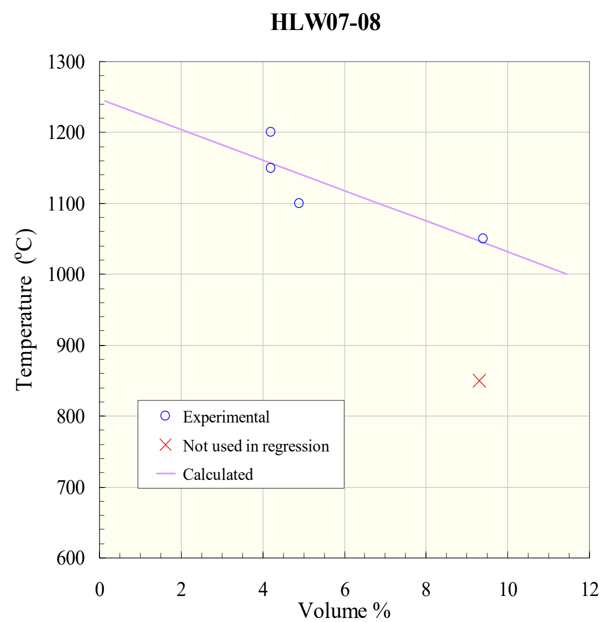


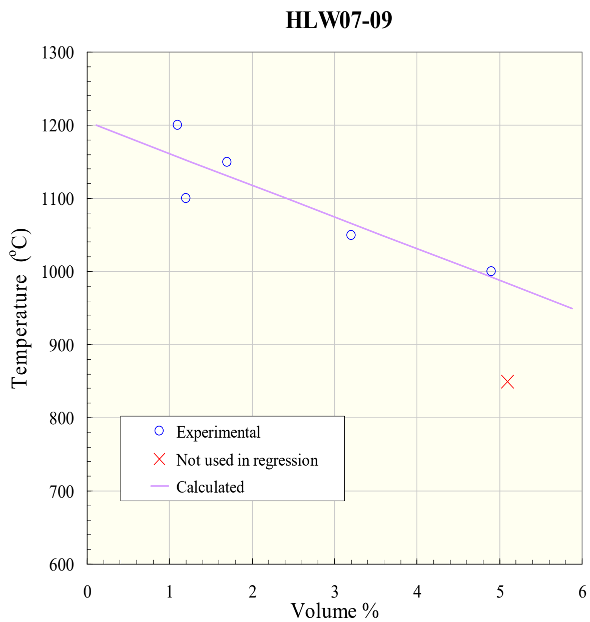
Note: Data point at (Vol % =25.0, T = 750 °C) is not shown and was omitted from regression

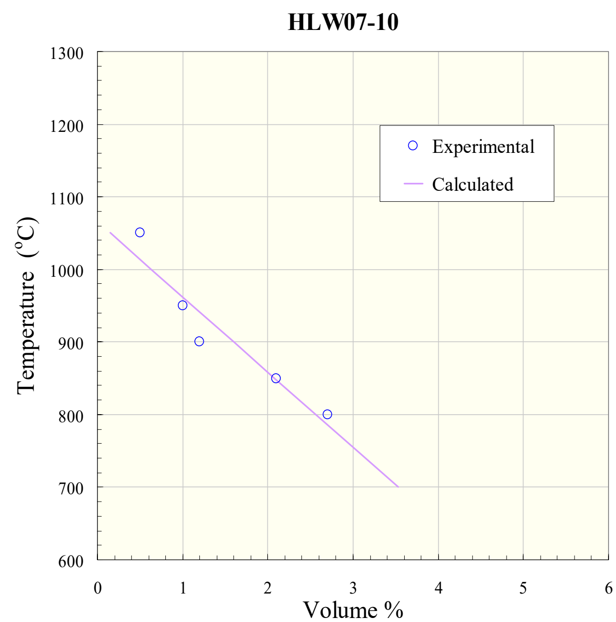

HLW07-05
Temperature (°C)
Volume %
Experimental
Calculated

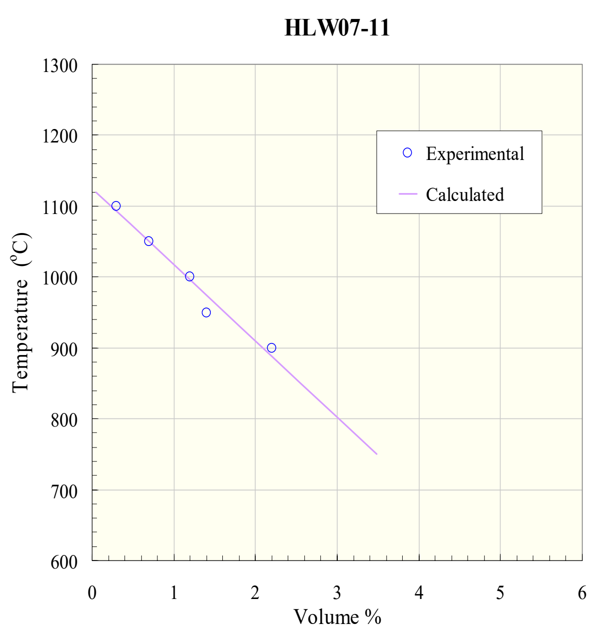

HLW07-06
Temperature (°C)
Volume %
Experimental
Calculated


HLW07-07
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated

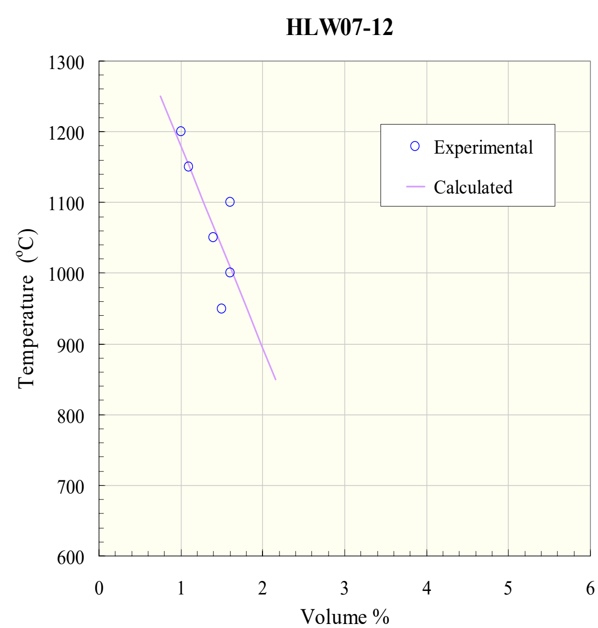

HLW07-08
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated



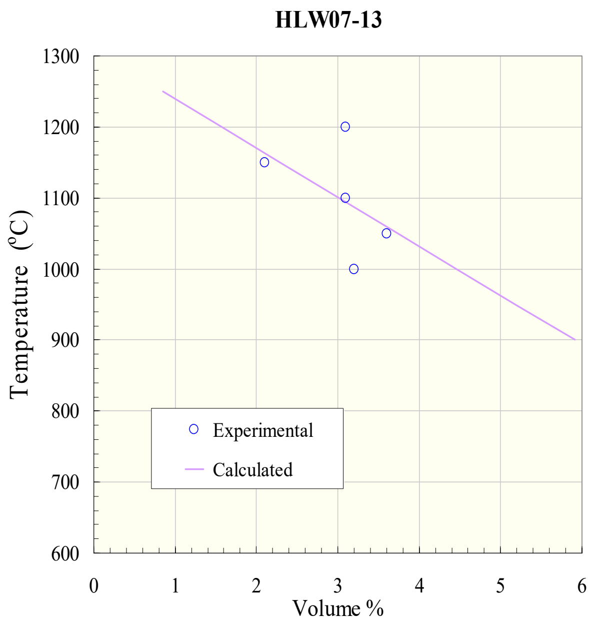


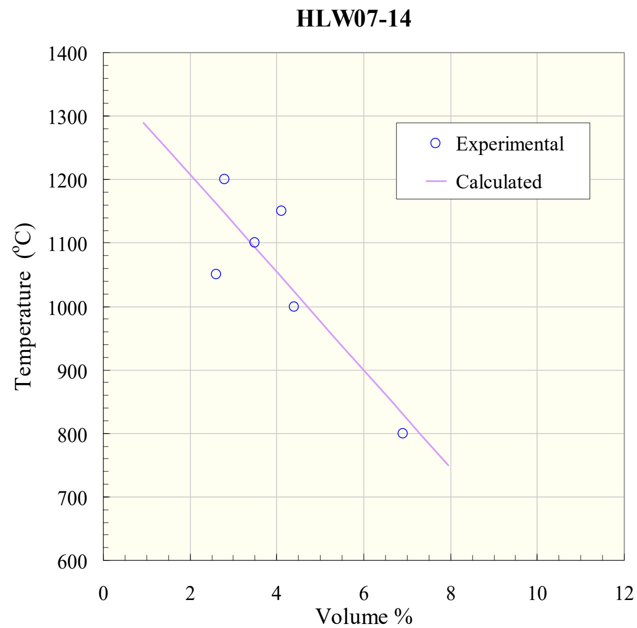


Note: Data point at (Vol % =13.8, T = 800 °C) is not shown and was omitted from regression

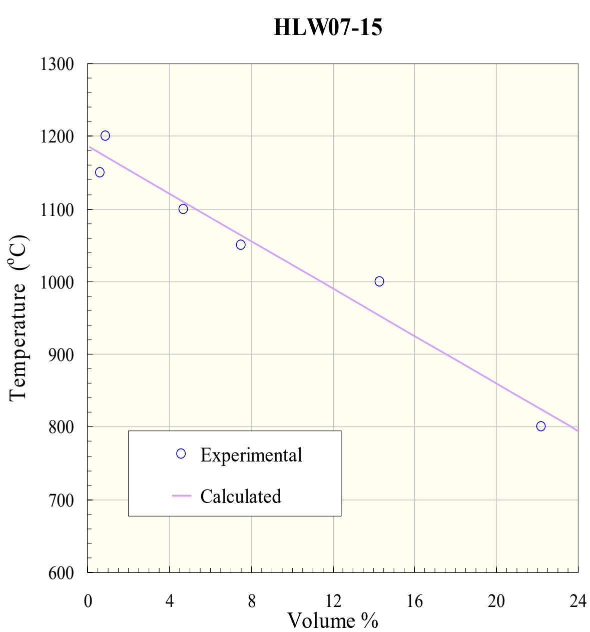


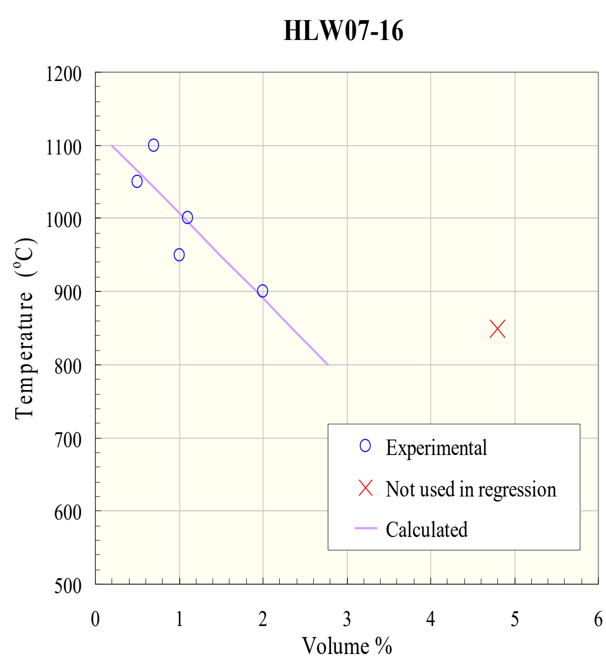
Note: Data point at (Vol % =24.9, T = 800 °C) is not shown and was omitted from regression

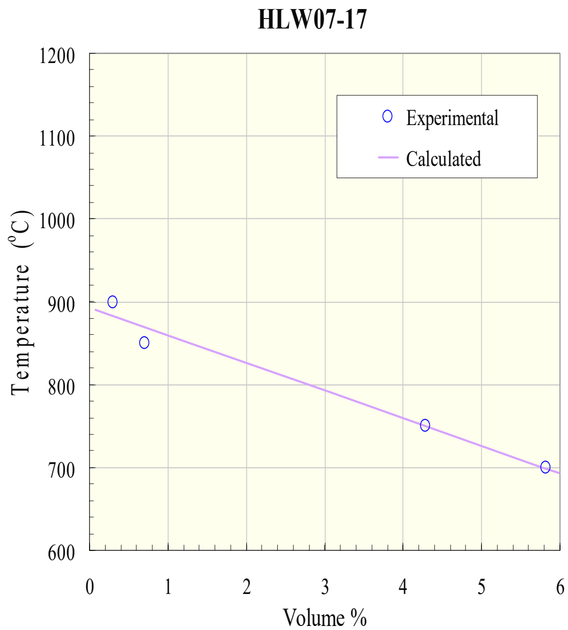


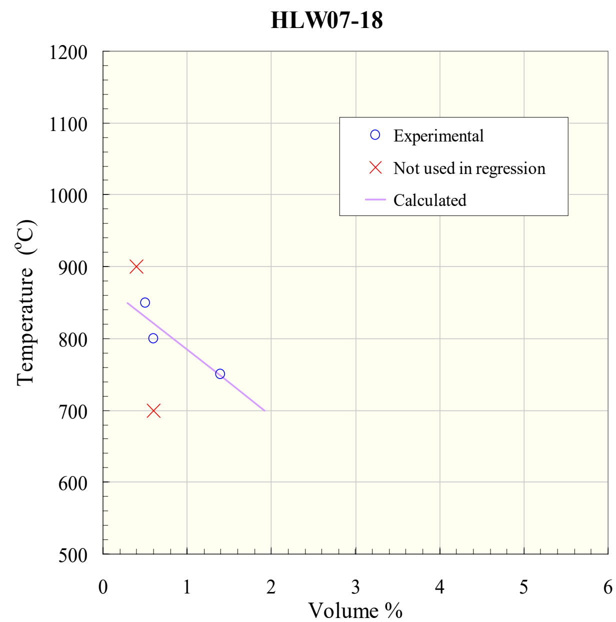


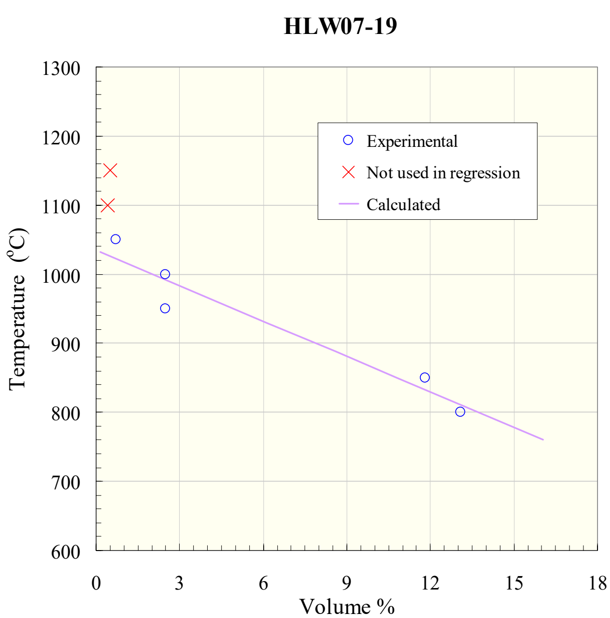
Note: Data point at (Vol % =21.1, T = 800 °C) is not shown and was omitted from regression

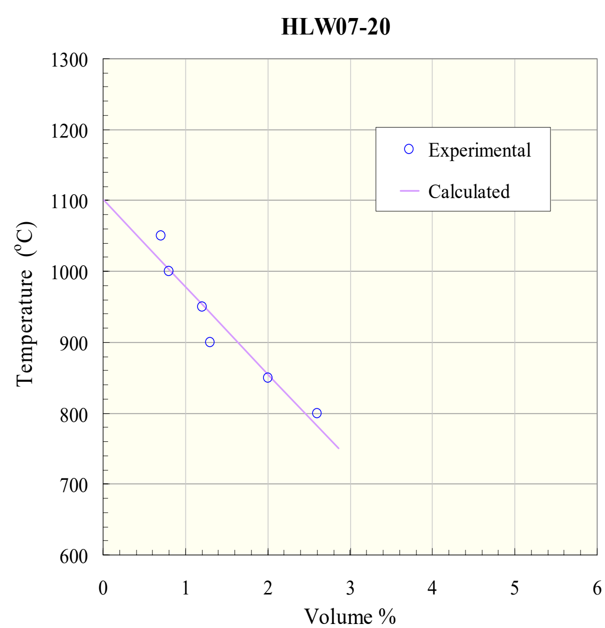




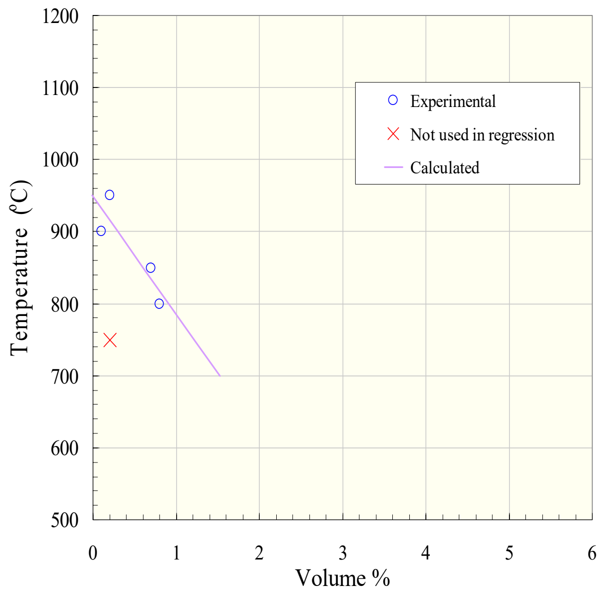

HLW07-17
Experimental
Calculated
Temperature (°C)
Volume %


HLW07-18
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %

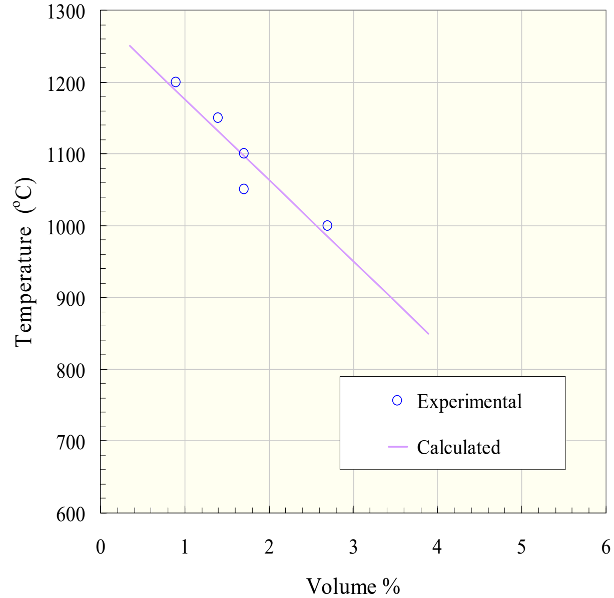

HLW07-19
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %


HLW07-20
Experimental
Calculated
Temperature (°C)
Volume %

HLW07-21

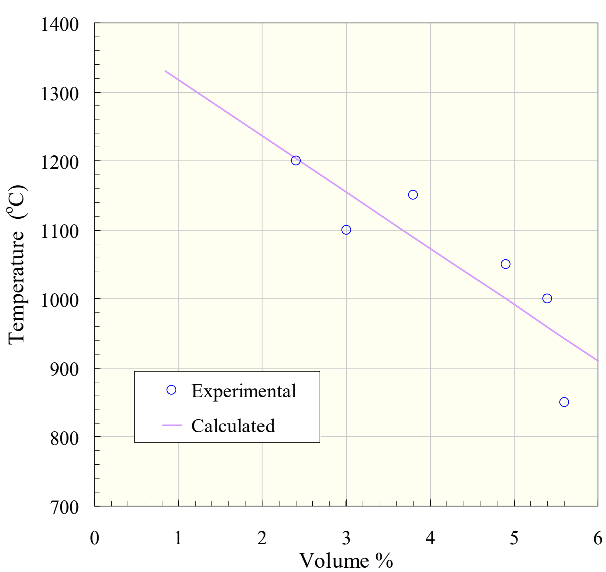


HLW07-22

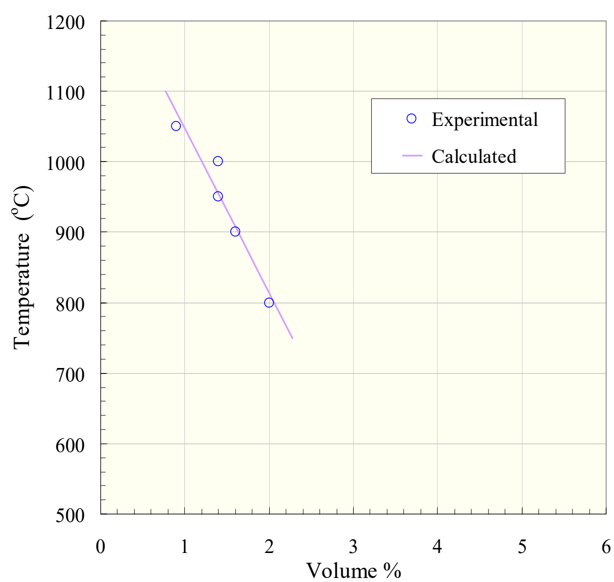


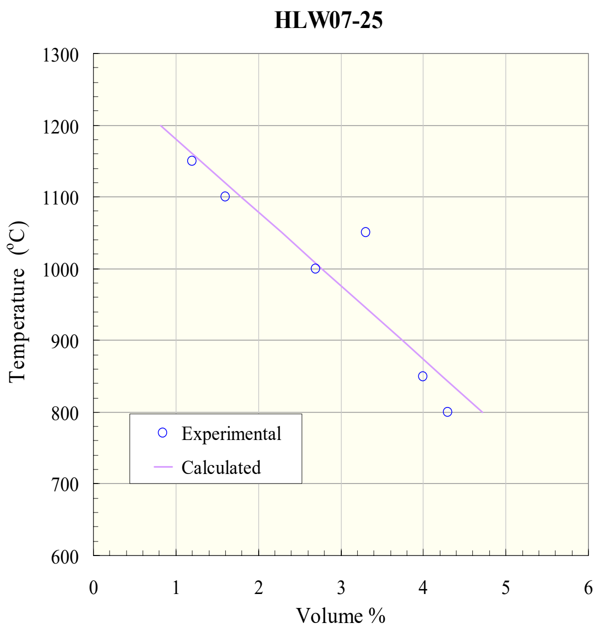
Note: Data point at (Vol % =13.0, T = 800 °C) is
not shown and was omitted from regression

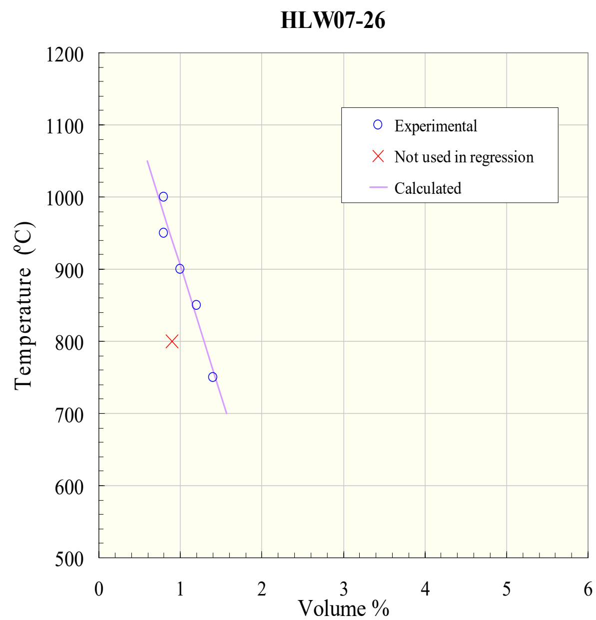
HLW07-23

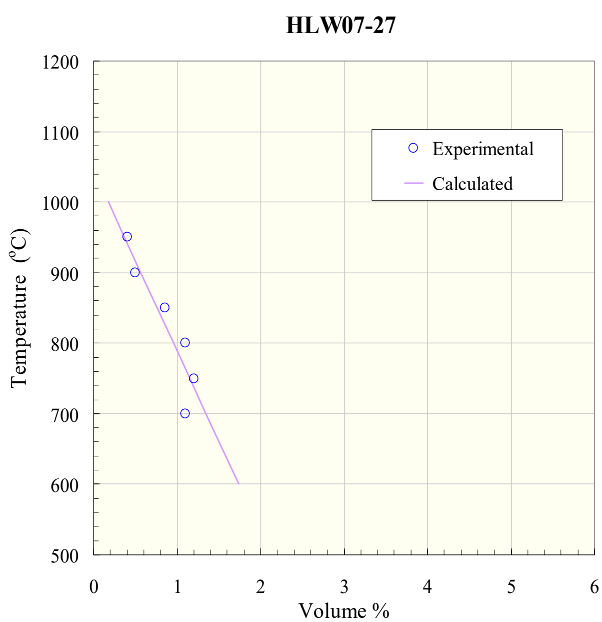


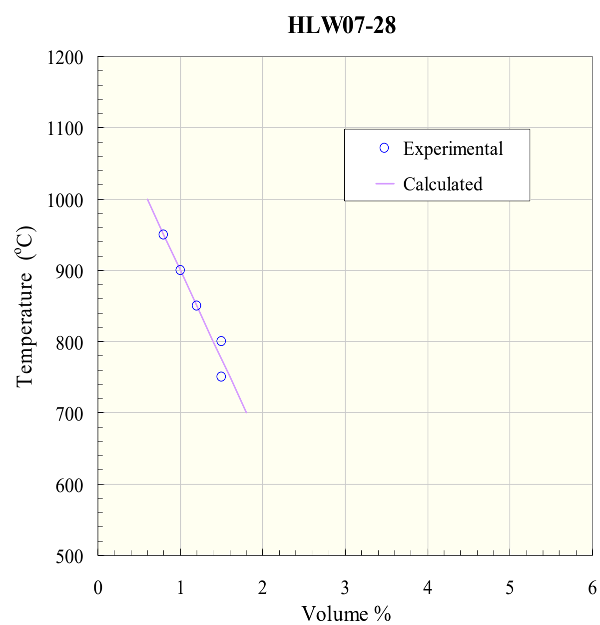
HLW07-24

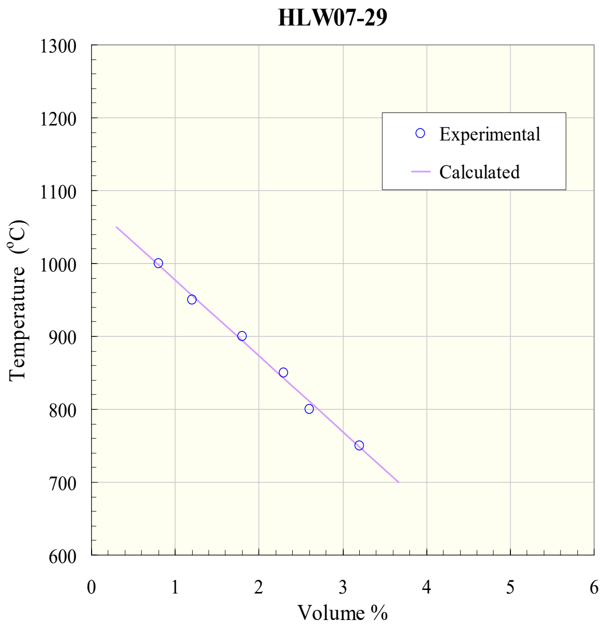


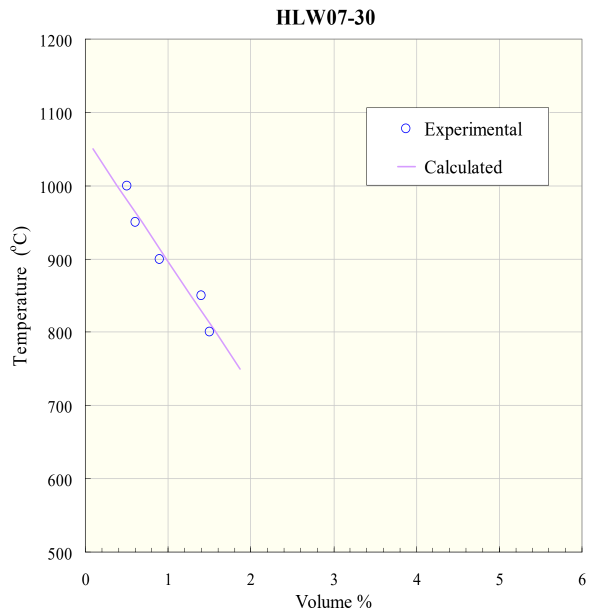

HLW07-25
Temperature (°C)
Volume %
Experimental
Calculated

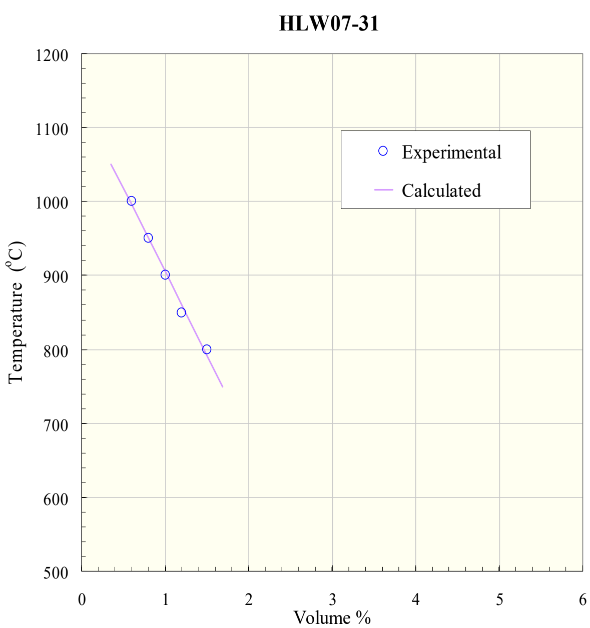

HLW07-26
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated

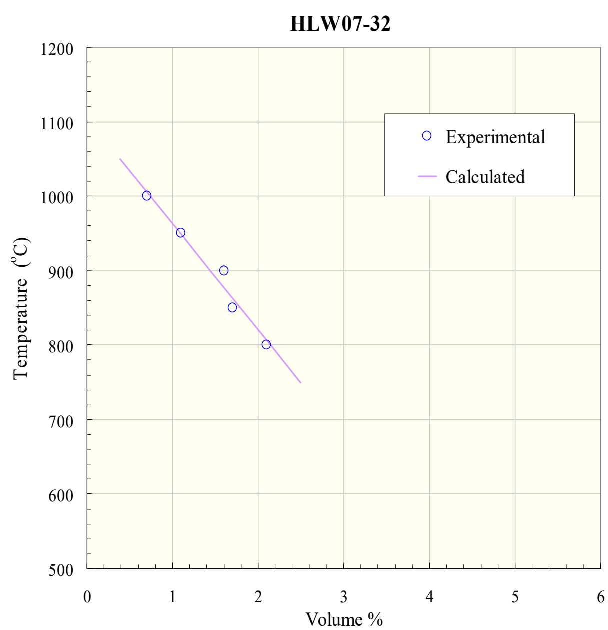

HLW07-27
Temperature (°C)
Volume %
Experimental
Calculated

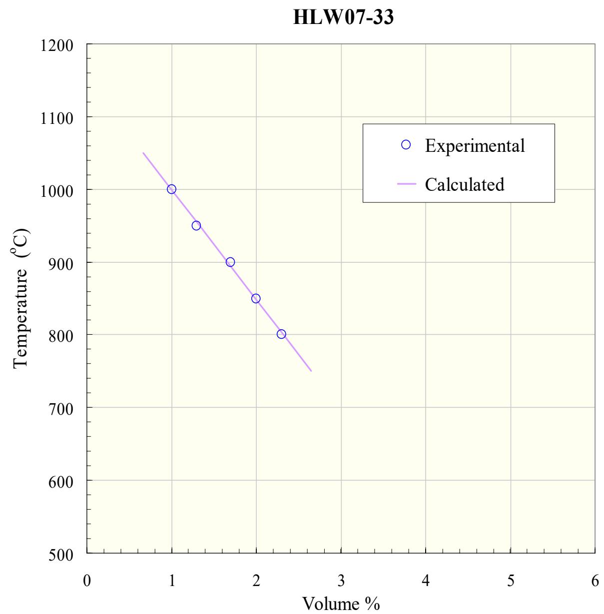

HLW07-28
Temperature (°C)
Volume %
Experimental
Calculated

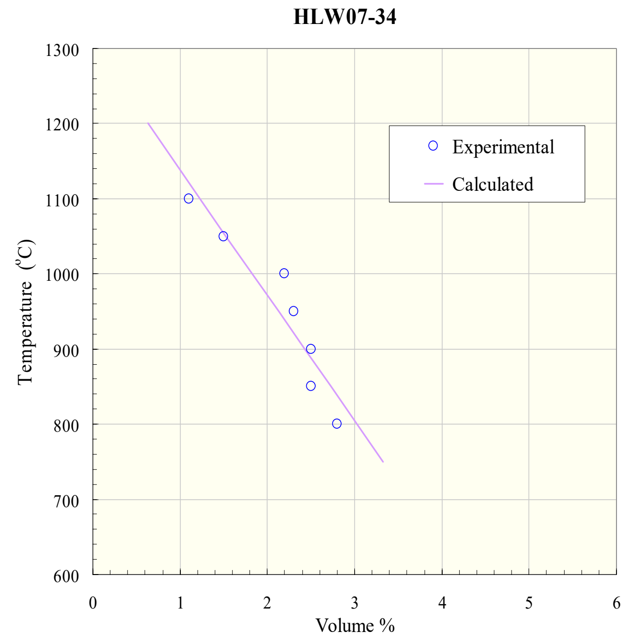

HLW07-29
Experimental
Calculated
Temperature (°C)
Volume %

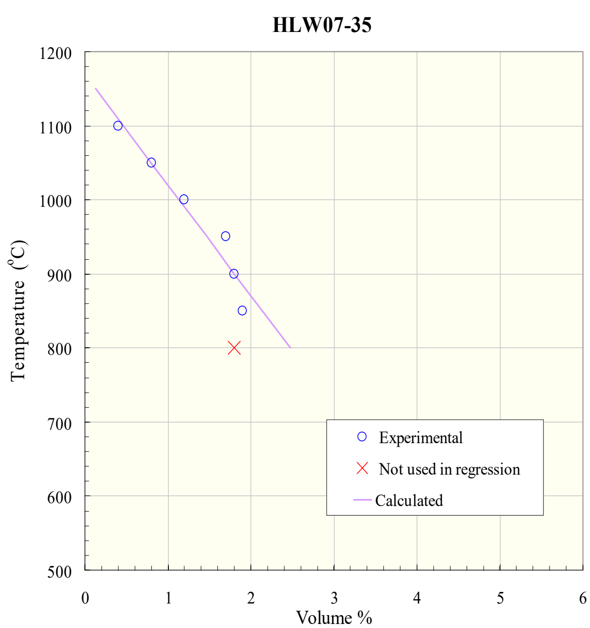

HLW07-30
Experimental
Calculated
Temperature (°C)
Volume %

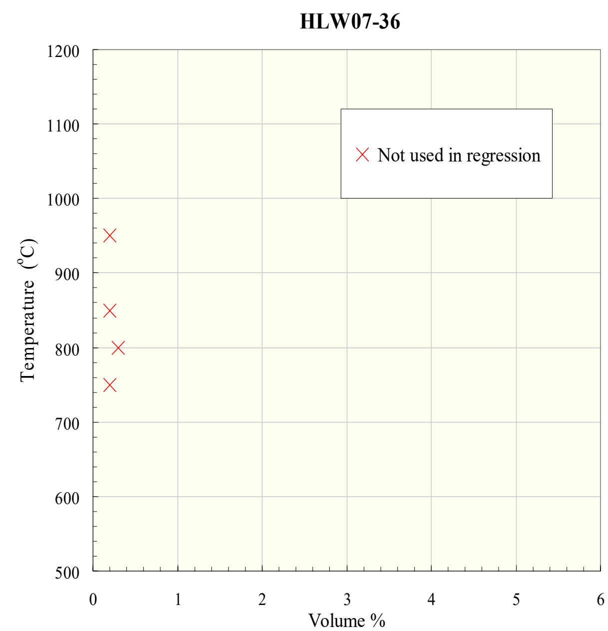

HLW07-31
Experimental
Calculated
Temperature (°C)
Volume %


HLW07-32
Experimental
Calculated
Temperature (°C)
Volume %

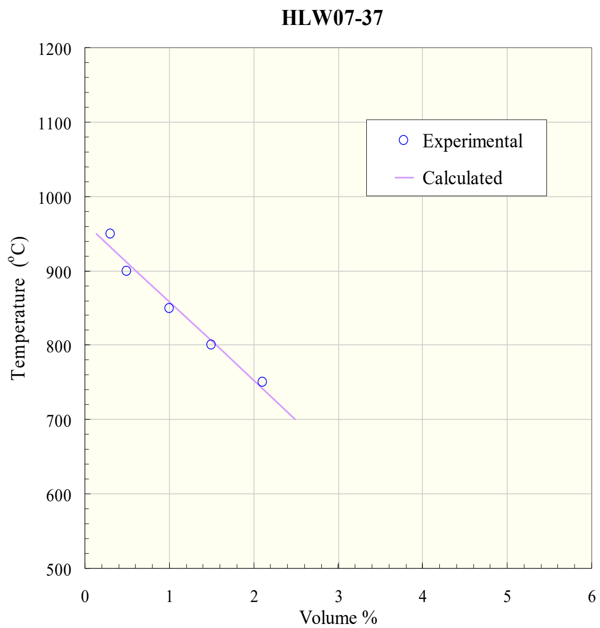


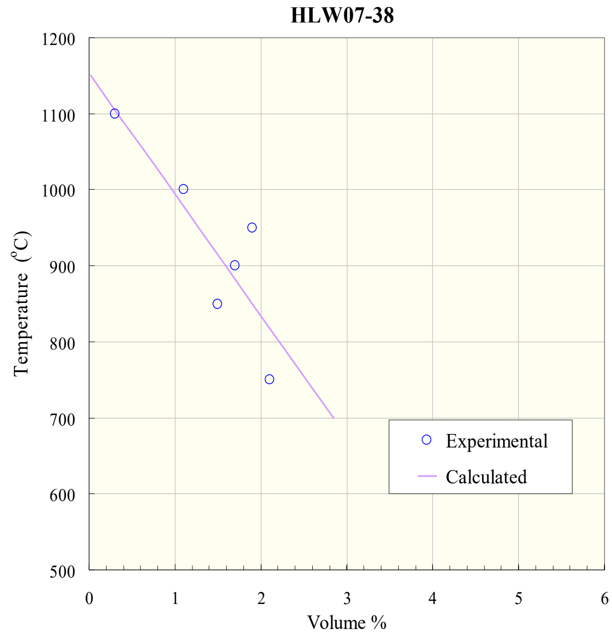


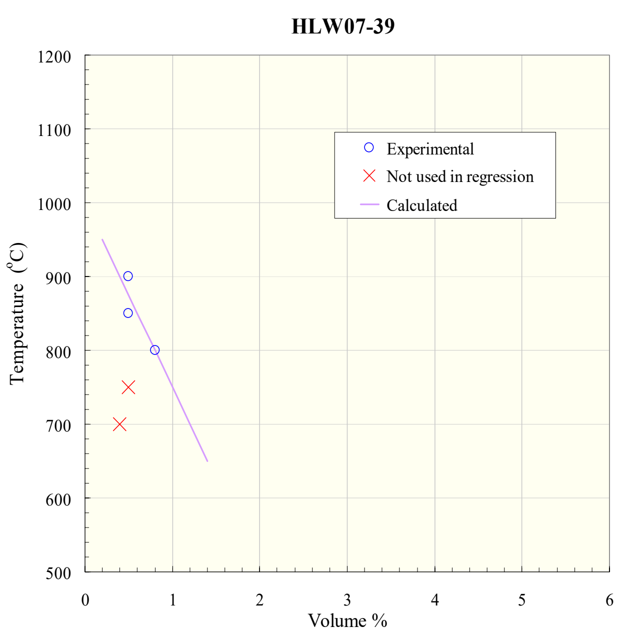


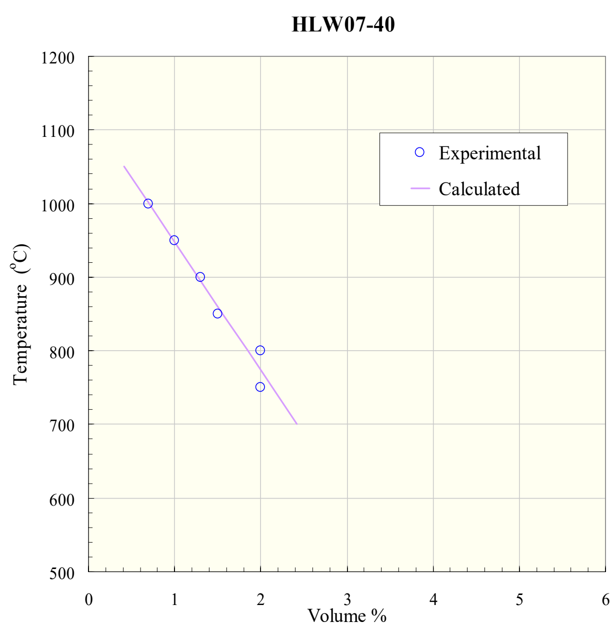


Note: Regression was not performed for HLW07-36.


HLW07-37
Temperature (°C)
Volume %
Experimental
Calculated


HLW07-38
Temperature (°C)
Volume %
Experimental
Calculated


HLW07-39
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated


HLW07-40
Temperature (°C)
Volume %
Experimental
Calculated