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PREPARATION AND TESTING (T1% AND PCT) OF HLW MATRIX GLASSES TO SUPPORT WTP PROPERTY-COMPOSITION MODEL DEVELOPMENT, VSL-05R5780-2, REV. 0

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

P.O. Box 550
Richland, Washington 99352

Approved for Public Release;
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VSL-05R5780-2

Final Report

Preparation and Testing ($T_{1\%}$ and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development

prepared by

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Completeness of Testing:

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

I.L. Pegg: [signature] **Date:** 10/12/05
VSL Program Director/Principal Investigator

I. Joseph: Innocent Joseph **Date:** 10-12-05
Duratek Sub-Contract Manager

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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
ID	Identification
IHLW	Immobilized High Level Waste
ILAW	Immobilized Low Activity Waste
LAW	Low Activity Waste
LRM	Low Activity Waste Reference Material
NQA	Nuclear Quality Assurance
PCT	Product Consistency Test
PNWD	Battelle—Pacific Northwest Division
QA	Quality Assurance
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
TWRS	Tank Waste Remediation System
VSL	Vitreous State Laboratory
WTP	Hanford Tank Waste Treatment and Immobilization Plant
XRF	X-ray Fluorescence Spectrometry

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 IHLW property-composition models for the River Protection Project-Waste Treatment and Immobilization Plant (RPP-WTP). Specifically, this report presents results of glass testing at VSL to support the development of IHLW Product Consistency Test (PCT) and one-percent crystal fraction temperature ($T_{1\%}$) models. The data will be used to augment and refine Phase 1 models during Phase 2 of the IHLW model development work. The Phase 2 IHLW PCT and $T_{1\%}$ models will be used to support qualification of the IHLW products. 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 35 glasses from a statistically designed matrix are presented in Section 4. The data cover a wider range than previously collected data for modeling. The IHLW PCT property-composition model will be augmented and refined using these data. The new models will be reported later.
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). Two matrices were developed and tested: a Spinel Matrix that focused on the AZ-101, AZ-102, and AY-102/C-106 wastes, and a Non-Spinel Matrix that targeted AY-101/C-104 wastes. The collected data, which are described in Section 4, will support refinement of the $T_{1\%}$-property model for spinel (as the principal phase) that had previously been developed and reported. Data have been collected and $T_{1\%}$ values were estimated for glasses that precipitated thorium- and zirconium-containing phases. However, models have not yet been developed to predict $T_{1\%}$ that involves thorium or zirconium as the major crystalline phase.
Constrain the WTP composition region for glass formulation testing to be performed.	Yes	Data collected on both Non-Spinel Matrix and Spinel Matrix glasses (65 total) will provide information to limit the glass compositional ranges to be studied in future during the Phase 2 modeling effort.

Other objectives in the Test Specifications and Test Plan 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. Models to predict viscosity and electrical conductivity of glass melts have also been developed and previously reported. 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 also 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 melt 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).

C) Results and Performance Against Success Criteria

The compositions used in this work were based on two statistically-designed matrices of glasses that together were composed of 65 HLW glasses (30 glasses from the Non-Spinel Matrix to focus on AY-101/C-104 wastes and 35 glasses from the Spinel Matrix to target AZ-101, AZ-102 and AY-102/C-106 wastes).

Only the Spinel Matrix glasses were characterized with respect to PCT. The measured PCT results varied from 0.126 g/l to 12.427 g/l for boron, 0.050 g/l to 7.231 g/l for sodium, and 0.196 g/l to 3.629 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, in spite of the fact that PCT constraints were not used in designing the Spinel Matrix. While it is desirable for the purpose of model development to include HLW glasses that exceed the reference glass in terms of PCT releases, that possibility may be limited indirectly by design constraints other than PCT releases (e.g., melt viscosity).

Of the 65 test matrix glasses, $T_{1\%}$ values could be estimated for 61, spinel being the dominant crystalline phase for both matrices. For the Non-Spinel Matrix, the estimated $T_{1\%}$ data span a wide range, from 684.6°C to 1301.5°C. The median $T_{1\%}$ is 972.6°C (average = 953.9°C), which can be compared with the WTP processing requirement of $T_{1\%} \leq 950$°C. For the Spinel Matrix, after exclusion of the three outliers, the $T_{1\%}$ values range from 844.2°C to 1279.1°C, with a median of 1070.2°C. This value is substantially higher than the median of 946.1°C determined for the previous $T_{1\%}$-modeling matrices.

The PCT 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 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 Non-Spinel Matrix and Spinel Matrix glasses were developed by applying statistical experimental design methods to optimally cover compositional regions defined by compositional ranges and 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 by considering a variety of inputs including waste compositions and glass properties.

The 65 test matrix glasses were fabricated and characterized with respect to composition, PCT responses (for the Spinel Matrix glasses only), and crystal formation (volume %) vs. heat-treatment temperature. Regression of the volume % crystal fraction data provided estimates of $T_{1\%}$. All 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 Spinel Matrix glasses and the leachates were analyzed by Direct Current Plasma-Atomic Emission Spectroscopy. The test 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 fraction.

F) Simulant Use

Waste simulants were not used in this work. All of the glasses were 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

Follow-on tests are planned as part of the Phase 2 model development effort, which will provide the final WTP models for the IHLW PCT and $T_{1\%}$ responses.

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. This waste is stored in underground tanks at the Hanford site. 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 glass testing conducted between November 2004 and June 2005. The work included the statistical design of two test matrices, fabrication of the matrix glasses, and characterization of the resulting glasses. The characterization included Product Consistency Test (PCT) response and determination of $T_{1\%}$, which is the temperature at which the volume fraction of crystals in equilibrium with glass melt equals 1%. A previous report [1] described the results from an earlier phase of testing on 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. The data presented in the present report will be used to augment and refine those models during Phase 2 model development, which is planned for 2005 through 2007.

This report is responsive to the Test Specification [2], Test Plan [3] and Test Exception [4] 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 [3], 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. Test Guidance [5, 6] provided by the WTP Project supplied additional information to direct the specific phase of testing reported herein.

1.1 Test Objectives

The objectives of the HLW glass property-composition modeling work as given in the Test Plan [3] are listed below along with the strategy to address them.

- *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 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.

  The PCT data presented in this report will be used by the WTP Project 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 [4], 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]. 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 are reported herein instead of T_L. The data reported here will be used to further refine models to predict $T_{1\%}$.

  As will be seen subsequently, 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 by the development of two test matrices of glass compositions, each focusing on the expected characteristic compositions of the two groups. This is the same approach used previously in developing the Phase 1 models [1].

- *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 the data were used to support the development of a TCLP cadmium release model. The data and the model have been reported previously [7].

- *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 [8].

- *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.

In addition to their use in directly supporting the development of property-composition models, the collected data will be important in revising future constraints in a phased approach to HLW glass formulation testing. Therefore, as described in the Test Guidance [5, 6], another objective of the tests reported here is to *constrain the WTP composition region for glass formulation testing to be performed*. Consequently, the data presented in this report will form the basis to design and direct future HLW glass formulations testing.

1.2 Test Overview

The development of PCT and $T_{1\%}$ 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 experimental glass composition regions (EGCRs) of interest

(ii) Statistical design of the test matrices

(iii) Fabrication of the test glasses in the test matrices

(iv) PCT and $T_{1\%}$ measurements of the fabricated glasses (the PCT was performed on the Spinel Matrix glasses, per WTP guidance [6])

(v) Investigation and selection of initial mathematical model forms

(vi) Detailed statistical analyses of the PCT and $T_{1\%}$ data to develop 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) through (iv) obtained at VSL, while analyses and modeling of the collected data will be performed and reported at a later time (PNWD will make use of the collected data to augment and refine previous IHLW models).

Development of the design constraints for the test matrices, which is described in Section 2, required a variety of considerations and inputs including waste compositions. As stated above, the target waste groups for this work are from the source tanks AZ-101, AZ-102, AY-102/C-106, and AY-101/C-104. Based on earlier HLW glass formulation studies [9], the primary crystalline phase for AZ-101, AZ-102, and AY-102/C-106 wastes is expected to be spinel, while thorium- and zirconium-containing phases likely will dominate for AY-101/C-104 waste. Consequently, two sets of constraints have been developed to address the different EGCRs of interest. Statistical experimental design based on the developed constraints, which is also described in Section 2, resulted in two test matrices: (i) a matrix that contained 30 HLW test glasses, which was termed the *Non-Spinel Matrix*, focused on AY-101/C-104 wastes, and (ii) a matrix with 35 HLW test glasses, which was termed the *Spinel Matrix*, focused on AZ-101, AZ-102, and AY-102/C-106 wastes.

After generation of the test matrices, the 65 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 crystal fraction determinations (as a function of heat-treatment temperature) for all 65 glasses and PCT for the 35 Spinel Matrix glasses. The collected heat-treatment data were then used to provide estimated one-percent crystal fraction temperatures ($T_{1\%}$) using regression. Fabrication and testing of the 65 matrix glasses are described in Section 3. Section 4 presents and summarizes the PCT and $T_{1\%}$ test data.

SECTION 2
DEVELOPMENT OF TEST MATRICES

In order to develop property-composition models, adequate property-composition data covering the EGCRs of interest are required. This section describes the development and generation of two test matrices to support the collection of the necessary data on the relevant properties. Section 2.1 summarizes the constraints used in designing the matrices, while Sections 2.2 and 2.3 describe, respectively, the development of the Non-Spinel Matrix and the Spinel Matrix. Section 2.4 presents the compositions of the matrix glasses generated.

2.1 Matrix Design Constraints

The two test matrices were designed to cover two regions of simulated HLW glass compositions (i.e., EGCRs). These EGCRs were developed to focus the modeling efforts on the different waste compositions expected of the initial WTP feed tanks. The first EGCR focused on wastes from C-104/AY-101, which contain considerable amounts of thorium and zirconium. The other EGCR targeted the wastes from tanks AZ-101, AZ-102, and C-106/AY-102 (with blended LAW pretreatment products), which are especially high in iron. The Non-Spinel Matrix explored the first EGCR, for which zirconium- and thorium-containing phases are the most important secondary phases at temperatures below the liquidus (T_L). In contrast, spinel is expected to be the most prevalent secondary phase for the second EGCR, which was addressed in the Spinel Matrix.

Design of the EGCRs involved inputs and considerations of many different kinds; they are summarized in the following sections.

2.1.1 Waste Composition Inputs and HLW Glass Composition Constraints

Unlike previous matrix design, which made use of multiple sources for waste composition inputs, the ranges of waste and glass compositions were primarily provided by the WTP Project [5, 6].

- For the C-104/AY-101 waste, WTP dynamic flowsheet model (G2) runs formed the bases of the compositions. The waste sludge was washed, caustic leached, and washed again at baseline efficiencies. Further, the Test Guidance [5] directed that the concentration limits of Na_2O and Al_2O_3 in glass be expanded (to 20 wt% for Na_2O) from earlier studies [1].

- For the Spinel Matrix, flowsheet model runs and the WTP Contract Specification 8.2.2.1 provided the limits for both major and minor glass components [10]. In particular, WTP directed that the current HLW glass composition region be expanded by increasing concentrations of Al_2O_3, Na_2O, SO_3, and other minor components [6]. Optimization of washing and leaching processes may result in increased concentrations of Al_2O_3, Na_2O, and SO_3 in the HLW glass.

- The division of glass constituents in matrix design is as follows:
  - Major oxides that significantly affect glass properties were treated as design variables.
  - Minor constituents were treated as either design constants or components of a grouped variable denoted as "Others".
  - Radioactive constituents (U and Th) were included in both matrices and treated as design variables in both matrices.

2.1.2 Waste Loading Constraints

Since the test matrices were designed to cover a much wider compositional range than earlier design efforts [1] and concentration limits were provided by the WTP Project for many glass components, waste loading was less important as a design constraint. However, waste loading was used in the Non-Spinel Matrix design to ensure extreme glass compositions would be excluded. Waste loading constraints were not necessary in the design of the Spinel Matrix.

The constraint was developed based on the requirements of Contract Specification 1.2.2.1.6, "Product Loading" [10]. The relevant requirement found in the specification was $Al_2O_3 + Fe_2O_3 + ZrO_2 \geq 21.0$ wt%. The waste loading constraint used in the Non-Spinel Matrix design was 18 wt% $< Al_2O_3 + Fe_2O_3 + ZrO_2 <$ 27 wt%.

It should be noted that the matrix constraints were based on the latest available waste data and process flowsheet information, as provided and authorized by the WTP Project. As a consequence, the matrices include glasses with Cr_2O_3 contents of up to 0.25 wt% (Non-Spinel Matrix) and 0.6 wt% (Spinel Matrix, which is above the Contract minimum component limit of 0.5 wt%) and SO_3 contents of 0.1 wt% (Non-Spinel Matrix) and 0.28 wt% (Spinel Matrix). Glasses with higher concentrations of Cr_2O_3 and SO_3 will be tested in subsequent modeling efforts if future flowsheet projections indicate that these components may limit waste loadings.

2.1.3 HLW Glass Property Constraints

The bases for glass property constraints used to define the EGCRs and to develop the test matrices are as follows:

- Part B1 data and property-composition models [8, 9, 11-13]

- Viscosity and electrical conductivity constraints were based on processing limits (see below).
- PCT constraints were based on the Defense Waste Processing Facility Environmental Assessment (DWPF EA) glass limits [14]. PCT constraints were applied only to the design of the Non-Spinel Matrix glasses.
- The spinel $T_{1\%}$ temperature constraint was an upper bound to limit crystallization in the Non-Spinel Matrix. Both lower and upper bounds were applied in the Spinel Matrix.
- A limit on TCLP releases was imposed to ensure reasonably realistic maximum TCLP matrix dissolution rates. The limit was based on a TCLP normalized boron release model, which was derived from an analysis of Part B1 data [9].
- For the Spinel Matrix, the zirconia liquidus temperature was an upper bound to limit crystallization. The model described by Plaisted et al. [15] was used to implement the constraint. For the Non-Spinel Matrix, the zirconia liquidus temperature was limited by both lower and upper bounds.
- Limits were not imposed on the liquidus temperature of thorium oxide or any other thorium-containing phases.

2.2 Development of the Non-Spinel Matrix

The Non-Spinel Matrix was statistically designed to address the crystallization of non-spinel phases for wastes from Tank C-104/AY-102 [5]. In addition to the nine glass components likely influential to crystallization of Zr/Th/U phases (i.e., Al_2O_3, B_2O_3, Fe_2O_3, Li_2O, Na_2O, SiO_2, ThO_2, UO_3, and ZrO_2), two variables relevant to crystallization of spinel phases, Cr_2O_3 and "Others," were introduced in the design (Table 2.1). Inclusion of these design variables would allow for variation of components relevant to spinel crystallization so that useful cyrstallinity data below a designated temperature (which could be reasonably constrained by the $T_{1\%}$ models developed in Phase 1) would be available in cases for which crystallization of Zr/Th/U-containing phases did not occur. Table 2.2 provides the compositions of the "Others" component. Along with the variable components, there is a group of constant components (denoted as "Constant") that total 5.5 wt%. The "Constant" components are present in constant amounts for every glass in the matrix; their composition was set to be representative of that expected for the HLW glasses for Tank C-104/AY-101. Table 2.3 lists the compositions of the "Constant" components. Table 2.4 provides the selected glass property constraints.

The lower and upper bounds of each of the eleven design variables were determined mostly by the project guidance [5] and previous experience in HLW glass formulation for wastes with high contents of zirconium and thorium (Table 2.1). A layered structure, as employed in the design of matrix glasses in an earlier study [16], was adopted, with glass compositions on one inner layer and one outer layer. It was also decided that the matrix should include a center glass composition and several replicate data points. The inner layer consists of 12 unique glasses plus two replicates, while the outer layer consists of 13 unique glasses plus two replicates and a center point, giving a total of 30 glasses for the matrix. The glass compositions of both layers were generated using the commercially available experimental design software, *Design-Expert* (version 6.0.10), the usage of which has been described before [16]. Briefly, the D-optimal criterion was used for selecting points in the constrained compositional space. Fourteen inner-layer glasses were generated first, which were then used as the augmentation basis for generation of the sixteen outer-layer glasses. The multivariate constraints such as those for waste loading, product performance (e.g., PCT, and TCLP), and vitrification processing (e.g., viscosity, electrical conductivity, and crystallinity) imposed in the design calculation are listed in Table 2.4. Although most of the constraints listed in Table 2.4 are self-evident, it is worth noting that $T_{1\%}$ of spinel was set to be below 850°C so as to avoid the complication of co-precipitation of both Zr/Th/U phases and spinel phases in the more important temperature region (i.e., >850°C).

Table 2.5 presents the resulting target compositions for the 30 Non-Spinel Matrix glasses (designated as the HLW05- series). Table 2.6 provides expansions of the “Others” and “Constant” components for each of the 30 glasses.

2.3 Development of the Spinel Matrix

One of the primary objectives of the development of the Spinel Matrix was to constrain the WTP composition region for future glass formulation testing [6]. As indicated in the project guidance [6], new data on spinel crystallinity and PCT must be developed to augment the data collected during Phase 1 [1] to accommodate the expanded composition boundaries. Of particular interest are Al_2O_3, Na_2O, SO_3, and other minor components (see Table 1 of Reference [6]). The upper boundaries of major and minor glass components are required to range up to or beyond the specified values, and the lower boundaries for many major and minor components are required to reach zero. In other words, the Spinel Matrix is intended to explore spinel $T_{1\%}$ and PCT responses in the expanded compositional region for follow-on work.

The scoping nature of the Spinel Matrix mandated that sufficiently broad composition ranges be covered with a limited number of points (35) to allow for a data-driven decision on EGCRs for future testing. A statistical approach similar to that used in Non-Spinel Matrix development was adopted to formulate Spinel Matrix glasses. The compositional ranges of the major glass components are summarized in Table 2.1. Note that the inner layer was designed to suppress crystallization of non-spinel phases (e.g., ThO_2, ZrO_2, $ZrSiO_4$) while extending the ranges of Al_2O_3 and Na_2O, while the outer layer encompassed wide ranges of all major glass components to reach the prescribed minima and maxima [6]. In addition to the ten glass components used in the design of the Non-Spinel glasses (i.e., Al_2O_3, B_2O_3, Fe_2O_3, Li_2O, Na_2O, SiO_2, ThO_2, UO_3, ZrO_2, Cr_2O_3), three oxides relevant to spinel crystallization (MnO, NiO, and ZnO) were introduced as independent variables. For the Spinel Matrix, there were two composite variables (“Others1” and “Others2”) and a “Constant” (Tables 2.2 and 2.3). Note that the makeup of the “Constant” components is different from that of the Non-Spinel Matrix, with the addition of two glass components that were not used in the Non-Spinel Matrix: Cl and Nd_2O_3.

Note also that Nd_2O_3 was included in both "Constant" and "Others1." "Others1" also includes SrO (the dominant member in the group), La_2O_3, CdO, and SO_3 (Table 2.2). "Others2" contains more common oxides for silicate glass systems. Finally, the composition of "Constant" was set on the basis of the required maxima of the representative or important waste constituents (except for Ag_2O).

The two-layered structure was again used for development of Spinel Matrix glasses. The inner layer consists of 18 unique glasses plus two replicates, and the outer layer consists of 14 unique glasses and a center point. Glasses of both layers were generated using the commercial experimental design software, *Design-Expert* (version 6.0.10) as described before [16]. Briefly, the D-optimal criterion was used for selection of points in the constrained compositional space. Twenty glasses of the inner layer (HLW06-01 to HLW06-20) were generated first. A database of broad composition coverage was then assembled for augmentation calculation of the outer-layer glasses. Table 2.7 summarizes the groups of HLW glasses used as the augmentation basis and the method used to adjust their original target compositions. In general, the glass compositions of the HLW02-, HLW03-, and HLW05- series were regrouped according to the 13 single oxide terms and two composite terms (Table 2.1). The totals of the 15 terms were then renormalized to be equal to 97.91 wt% for the identical constant 2.09 wt% as for HLW06 glasses. The 152 existing HLW formulations after renormalization (102 from HLW02 and HLW03; 30 from HLW05 and 20 from the inner layer of HLW06) formed the basis of the augmentation calculation for the generation of the 15 outer-layer glass formulations of the Spinel Matrix.

The multivariate constraints in the design made use of results from earlier studies and involved only those regarding vitrification processing (e.g., viscosity, electrical conductivity, and crystallinity, see Table 2.4). The performance related constraints, such as PCT and TCLP were not used because of their relative ineffectiveness in restricting the data placement in compositional space. The liquidus of ZrO_2 was set to a relatively high temperature of 1420°C because: 1) Since no model was available for reliably constraining the $T_{1\%}$ of the Zr-, or Th-related phases for WTP glasses, the ZrO_2 liquidus constraint was employed only "loosely"; and 2) Using a lower ZrO_2 liquidus constraint tended to result in poorer distributions of the predicted viscosity, electrical conductivity, and total alkalis for the generated 35 HLW06 glasses. In general, a more uniform distribution is favored in statistical design, especially in light of future modeling work for which the data would be used.

Tables 2.8 and 2.9 present the Spinel Matrix target glass compositions. The chemical compositions of the Spinel Matrix and the Non-Spinel Matrix as a group are easily distinguishable from those of previous modeling matrices (i.e., Initial Matrix and Augmentation Matrix [1]) by their considerably extended ranges in two major components: Al_2O_3 and Na_2O. The increases (up to about 5 wt%) in both oxides are expected to greatly impact various properties of the glasses, with the effects on crystallization of spinel and Zr/Th-rich phases to be evaluated in the upcoming modeling study. Another compositional region covered by the current matrices overlaps that which is typical of LAW glass formulations (i.e., Na_2O at 20 wt% and Li_2O at 0 wt%). Finally, the higher concentrations of ZrO_2 and Cr_2O_3, compared to those found in earlier matrices [1], appreciably extend the database for development of property-composition models.

SECTION 3
EXPERIMENTAL PROCEDURES

After completion of the statistical design of the Non-Spinel Matrix (30 glasses, including replicates) and the Spinel Matrix (35 glasses, including replicates), these glasses were fabricated at VSL on a crucible scale (about 420 grams). The resulting glass products were then sub-divided into portions that were used for the various tests, including PCT and $T_{1\%}$ determination. The experimental procedures employed in preparing and characterizing the 65 IHLW glasses are summarized in this section.

3.1 Glass Batching and Preparation

All HLW test glasses were fabricated at VSL using reagent grade chemicals and solutions of known purity. The Technical Procedure *Crucible Melts* [17] 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 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 [9, 18], which suggested that thallium loss may vary with concentration and glass composition. On the 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 Non-Spinel Matrix glasses (thallium is not part of the Spinel Matrix design).

In batching recipes for preparing these HLW glasses, up to 32 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 16 (for the Non-Spinel Matrix) or 8 (for the Spinel Matrix) components that were prepared with reagent grade chemicals 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 (which consisted of ruthenium (Ru), rhodium (Rh), and palladium (Pd) in nitric acid) 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. 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 Analyses of Glass Composition

Compositions of the prepared HLW glasses were analyzed with x-ray fluorescence (XRF) spectroscopy. 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 NIST, as well as waste glasses including the Argonne National Laboratory–Low Activity Waste Reference Material (ANL-LRM) and the DWPF-EA glass.

3.3 Product Consistency Test

The PCT data for the Spinel Matrix glasses were collected at VSL from tests performed at 90°C for 7 days according to ASTM C1285 [19], as required in Specification 1 of the WTP contract [10]. Samples of crushed glasses (4 g, 100-200 mesh, or 75-149 μm) were placed in 40 ml of test solution (de-ionized water) inside 304L stainless steel vessels. All tests were conducted in triplicate, and in parallel with the 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 concentrations c_i measured in the leachate (in ppm) as:

$$r_i = \frac{c_i}{f_i} \ , \qquad (3.1)$$

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:

$$L_i = \frac{r_i}{(S/V)} \ , \qquad (3.2)$$

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), normalized leachate concentration (g/l), normalized mass loss (g/m^2), and normalized 7-day leach rate ($g/(m^2\text{-day})$).

Specification 1 of the WTP contract requires that the normalized mass losses of B, Na, and Li in PCT be below the respective values for the DWPF-EA glass. The nominal values for normalized leachate concentrations from the DWPF-EA glass are 16.695, 13.346, and 9.565 g/l for B, Na, and Li, respectively [14]. The corresponding value for Si is 3.922 g/l.

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

Glass samples (about 5 grams each) were heat-treated in a platinum, platinum-gold, or platinum-rhodium crucible (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 examination (Model JSM-5910LV, equipped with Oxford Instruments INCAEnergy 300 system) determined the volume fraction of crystalline phases and the identification of 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 very small.

SECTION 4
PROCUCT CONSISTENCY TEST (PCT) AND ONE-PERCENT CRYSTAL FRACTION TEMPERATURE ($T_{1\%}$) RESULTS

This section presents the characterization and test data of 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 the Spinel Matrix glasses (35 glasses) and the data are discussed in Section 4.2. Section 4.3 presents the heat-treatment data for both the Spinel Matrix and Non-Spinel Matrix glasses (35 and 30 glasses, respectively). Section 4.3 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 Spinel Matrix and Non-Spinel Matrix glasses are given in Tables 4.1 and 4.2, respectively. Note, however, that the batched (target) compositions were used below for calculating normalized PCT responses (and for future modeling efforts) since they were 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.

As can be seen in Tables 4.1 and 4.2, the analyzed compositions for the major components generally show good agreement with the targets. However, for selected minor components, especially barium, some discrepancies are evident. For example, analysis of HLW06-24 showed no presence of BaO, even though the target value was relatively high at 0.3 wt%. The “non-detect” for barium was traced to spectral interferences from other components, chiefly strontium in this case. Even though the presence of barium was actually detected (at > 0.2 wt%), the analytical software reported that as insignificant because of the high background due to strontium. No attempts were made to alter the detection and analysis algorithm of the software.

4.2 Product Consistency Test (PCT) Results

The data for PCT releases of boron, lithium, sodium, and silicon for the 35 Spinel Matrix glasses are listed in Table 4.3. The 30 Non-Spinel Matrix glasses were not tested with respect to PCT. The PCT results are presented as leachate concentrations (in ppm), normalized glass mass loss (in g/l and g/m^2), and normalized leach rate (in $g/(m^2\text{-day})$). Normalized PCT releases were calculated using target mass fractions in glass. Figure 4.1 shows the normalized PCT boron, lithium, and sodium releases for all 35 glasses. As seen in the figure, glasses from the outer layer of the design (HLW06-21 through -34) show considerably more scattered and extreme PCT releases, a reflection of the expanded compositions explored in the outer layer. However, all the measured PCT responses are well below the nominal values for the reference glass DWPF-EA; the normalized boron PCT releases range from 0.126 g/l to 12.427 g/l, compared with 16.695 g/l for DWPF-EA. For sodium and lithium, the ranges of measured normalized PCT releases are, respectively, 0.050 g/l to 7.231 g/l and 0.196 g/l to 3.629 g/l, compared with the corresponding nominal values of 13.346 g/l and 9.565 g/l for the DWPF-EA glass. Unlike the designs used for previous modeling [1], compliance with IHLW PCT performance requirements was not part of the property constraints for the current tests (see Section 2). Thus it is seen that, although it may be desirable for the purpose of model development to include IHLW glasses that span a wider range of PCT performance, formulation of glasses with higher PCT responses may be indirectly limited by other property constraints (e.g., viscosity).

Two pairs of replicate compositions were designed into the Spinel Matrix (i.e., HLW06-01 = HLW06-17 and HLW06-06 = HLW06-13, compositionally). The glasses were then fabricated and tested in the same way as the other matrix glasses in random order. Table 4.4 identifies these two replicate pairs and gives the associated PCT data. The calculated relative standard deviations (%RSD) in Table 4.4 suggest that the agreement between the replicates is reasonably good and generally comparable to those from previous tests. The results for boron show much smaller %RSD than the PCT data from Phase 1 modeling tests [1]; the pooled %RSD for sodium PCT releases is also slightly smaller. The calculated %RSD for the PCT releases of sodium is also similar to the values (about 10%) reported in another study (Table F.5 in Reference [20]), while the corresponding values for boron and lithium in Table 4.4 (15% and 19% respectively) are somewhat larger than the approximately 10% RSD values reported in Reference [20].

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 7 sets of testing. The %RSDs in Table 4.5 are comparable to or better than those reported previously [14]. They are also 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 measured PCT release of sodium, however, is somewhat lower than the nominal value.

4.3 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, at selected temperatures that were at least 50°C apart. Tables 4.6 and 4.7 list, respectively, the measured crystal vol% data for the Non-Spinel Matrix and Spinel Matrix glasses. Fitting of these data to a regression equation of the form

$$T = a_0 + a_1 X, \qquad (4.1)$$

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. Tables 4.8 (Non-Spinel Matrix) and 4.9 (Spinel Matrix) present 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 4.2 shows the distribution of the estimated $T_{1\%}$ for both matrices. Figures 4.3 and 4.4 are, respectively, histograms of the estimated $T_{1\%}$ values for the Non-Spinel Matrix and Spinel Matrix. Appendix A includes plots of the experimental data and the calculated regression results for all 65 glasses.

As can be seen in the plots of vol% crystals against heat treatment temperature (Appendix A), the typical relationship 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 of vol% is non-linear. For example, the data for the replicate pair HLW05-02 and HLW05-07 (similarly for the replicate pair HLW05-18 and HLW05-28) show a change of sign of the slope, presumably because increases in melt viscosity at lower temperatures reduce the rate of crystallization, preventing the system from reaching equilibrium during the experimental duration (70 hours). In a few other cases (e.g., HLW05-19), the data show an abrupt change of slope, characteristic of the appearance of a second phase. 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 Tables 4.8 to 4.9 and Appendix A).

Overall, $T_{1\%}$ was estimated for 61 of the 65 glasses; the other 4 glasses (all from the Non-Spinel Matrix) did not show sufficient crystallization even at low temperatures to allow estimation of $T_{1\%}$. Among the Non-Spinel Matrix glasses, the estimated $T_{1\%}$ show a fairly wide range of 684.6°C to 1301.5°C, which can be compared with the range of (554.2 − 1247.8)°C found for the earlier $T_{1\%}$-modeling study, which included many more glasses (102 total) [1]. The median $T_{1\%}$ is 972.6°C (average = 953.9°C), which can be compared with the WTP processing requirement of $T_{1\%} \leq 950$°C. The major crystalline phases observed also show a good deal of variation: spinel, thorium oxide, zirconium oxide, zirconium silicate, $Na_2ZrSi_2O_7$ (compositionally identical to parakeldyshite), uranium oxide, and a sodium/aluminum silicate that was not fully characterized. In spite of employing the constraint of $T_{1\%}$(spinel) < 850°C to limit its formation, spinel is the most prevalent phase observed, especially in the inner layer. Of the 30 Non-Spinel Matrix glasses, only 17 show a non-spinel predominant phase at the estimated $T_{1\%}$.

Spinel is, not surprisingly, also the most prevalent crystalline phase found for the Spinel Matrix; all 20 inner-layer glasses form spinel as the principal phase during heat treatment (ZrO_2 is the most important minor phase), whereas 5 of the 14 outer-layer glasses exhibit the same behavior (ThO_2, ZrO_2, $ZrSiO_4$, $Na_2ZrSi_2O_7$, and an unidentified chromium/iron oxide are the major phases for the other glasses). The estimated $T_{1\%}$ values range from 650°C to 1481.4°C (Table 4.9). Among the 35 estimated $T_{1\%}$ values, three outliers were obtained through large extrapolations (e.g., HLW06-22, -26, and -27). With exclusion of those three glasses, the $T_{1\%}$

values range from 844.2°C to 1279.1°C. The median is 1070.2°C (average = 1084.4°C), which is substantially higher than that determined for the Phase 1 modeling matrices (946.1°C in Reference [1]). This suggests that the current data form a good supplement to the earlier data, providing additional coverage in glass composition regions with higher $T_{1\%}$, since relatively few samples with $T_{1\%} > 1000$°C resulted from the earlier matrix design [1]. The histogram of the estimated $T_{1\%}$ values (Figure 4.4) graphically demonstrates the extended coverage range of the current data.

Table 4.10 lists the replicate pairs of glasses in the two matrices, the corresponding estimated $T_{1\%}$ values, and pairwise as well as pooled standard deviations (SDs) based on the replicate pairs. The pooled SD of 20.79°C shows that the current tests were subject to somewhat lower variation than the Phase 1 modeling tests (pooled SD = 26.06°C [1]).

SECTION 5
SUMMARY

In order to augment earlier IHLW property-composition modeling work [1] and to constrain the WTP HLW glass composition region in future studies, statistical designs were used to develop two matrices of HLW glass formulations for testing. The Non-Spinel Matrix, which focuses on an Experimental Glass Composition Region (EGCR) that is likely to precipitate solid phases other than spinel (primarily zirconium- and thorium-containing phases) when cooled to below liquidus temperature, consists of 30 glasses. The Spinel Matrix targets spinel as the major crystalline phase and consists of 35 glasses. The 65 matrix glasses were prepared at VSL using a procedure similar to one that was used previously in model development [1].

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 analysis.

The Spinel Matrix glasses were subjected to the 7-day PCT at 90°C. The measured PCT releases encompass a wider range than in the previous PCT-modeling study [1]: normalized releases varied from 0.126 g/l to 12.427 g/l for boron, 0.050 g/l to 7.231 g/l for sodium, and 0.196 g/l to 3.629 g/l for lithium. However, all 35 matrix glasses still outperformed the reference DWPF-EA glass, in spite of the fact that PCT constraints were not used in designing the matrix. While it is desirable for the purpose of model development to include HLW glasses that exceed the reference glass in terms of PCT releases, that possibility may be limited indirectly by design constraints other than PCT releases (e.g., melt viscosity).

Glasses from both the Non-Spinel Matrix and the Spinel Matrix underwent isothermal heat treatment. Regression of the heat-treatment data provided estimates of $T_{1\%}$. For the Non-Spinel Matrix, $T_{1\%}$ values could be estimated for 26 of the 30 glasses. Although the design constraint of $T_{1\%}$(spinel) < 850°C was used to limit its formation, spinel was the most prevalent crystalline phase observed. Only 17 of the 30 matrix glasses showed non-spinel predominant phases at their respective estimated $T_{1\%}$ and a variety of phases was observed, including ThO_2, ZrO_2, $ZrSiO_4$, and $Na_2ZrSi_2O_7$.

For the Spinel Matrix, $T_{1\%}$ values were estimated for all 35 glasses, 3 of which were obtained by large extrapolations and were identified to be outliers. After exclusion of the three outliers, the $T_{1\%}$ values range from 844.2°C to 1279.1°C, with a median of 1070.2°C. This value is substantially higher than the median of 946.1°C determined for the previous $T_{1\%}$-modeling matrices [1], which suggests that the current data, with many more high $T_{1\%}$ values, may form a good supplement to the earlier data. Not surprisingly, spinel was by far the most prevalent crystalline phase and was observed as the major phase in 25 of the 35 glasses.

SECTION 6
QUALITY ASSURANCE

This work was conducted under a quality assurance program compliant with NQA-1 (1989) and NQA-2a (1990) subpart 2.7, and the *Quality Assurance Requirements and Description* (QARD) Document (DOE/RW-0333P, Rev. 13) [21]. This program is supplemented by a Quality Assurance Project Plan for RPP-WTP work performed at VSL [22]. 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 [23].

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
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Table 2.1. Components and Constraints for the Non-Spinel and Spinel Test Matrices.

Glass Components	Non-Spinel Matrix				Spinel Matrix			
	Inner Layer (wt%)		Outer Layer (wt%)		Inner Layer (wt%)		Outer Layer (wt%)	
Al_2O_3	6	10	2	13	8	11	1.88	13
B_2O_3	7	12	4.5	14	6.5	11	4.3	15
Fe_2O_3	5	8	1.5	12	7	14	1.4	15
Li_2O	3	5	0	6	0.25	3	0	6
Na_2O	8	16	6.5	20	14	20	3.7	20
SiO_2	38	44	34	49	35	40	33	53.1
ThO_2	3	4.5	1.5	6	0.25	1.5	0	5.94
UO_3	2.5	4.5	1	6.5	0.75	4	0	6.5
ZrO_2	5	10.5	2.5	11.5	1.5	4	0	11.5
Cr_2O_3	0.1	0.2	0.05	0.25	0.25	0.5	0	0.6
MnO	*included in "Others"*				1	4	0	8
NiO	*included in "Others"*				0.6	1	0	1.2
ZnO	*included in "Constant"*				1.5	2.5	0	4
"Others"	0.5	1	0.2	2	NA	NA	NA	NA
"Others1"	NA[1]	NA	NA	NA	2	6	0	14
"Others2"	NA	NA	NA	NA	1	6.02	0	6.02
"Constant"	5.5		5.5		2.09		2.09	

[1]NA = Not applicable.

Table 2.2. Compositions of Components Grouped as "Others" for the Non-Spinel Matrix and as "Others1" and "Others2" for the Spinel Matrix.

Non-Spinel Matrix				Spinel Matrix			
	Component	**Relative %**	**Maximum wt% in Glass**		**Component**	**Relative %**	**Maximum wt% in Glass**
Others	CdO	25	0.50	Others1	CdO	11.76	1.65
	MnO	50	1.00		La_2O_3	8.82	1.23
	NiO	25	0.50		Nd_2O_3	3.94	0.55
	Subtotal	100	2.00		SO_3	2.00	0.28
					SrO	73.48	10.29
					Subtotal	100.00	14.00
				Others2	BaO	4.98	0.3
					CaO	16.61	1
					K_2O	27.24	1.64
					MgO	19.44	1.17
					PbO	15.12	0.91
					TiO_2	16.61	1
					Subtotal	100.00	6.02

Table 2.3. Composition of "Constant" Components for the Non-Spinel and Spinel Test Matrices.

Component	Non-Spinel Matrix		Spinel Matrix	
	Relative %	Wt% in Glass	Relative %	Wt% in Glass
Ag_2O	1.82	0.1	4.78	0.1
BaO	9.09	0.5	*included in "Others2"*	
Bi_2O_3	3.64	0.2	14.35	0.3
CaO	13.64	0.75	*included in "Others2"*	
Cl	*not included in the matrix*		9.57	0.2
F	0.91	0.05	21.05	0.44
K_2O	3.64	0.2	*included in "Others2"*	
La_2O_3	9.09	0.5	*included in "Others1"*	
MgO	1.82	0.1	*included in "Others2"*	
Nd_2O_3	*not included in the matrix*		11.96 [1]	0.25
P_2O_5	5.45	0.3	23.92	0.5
PbO	0.27	0.15	*included in "Others2"*	
PdO	0.05	0.02	5.74	0.12
Rh_2O_3	7.27	0.04	2.39	0.05
RuO_2	0.36	0.02	6.22	0.13
SO_3	1.82	0.1	*included in "Others1"*	
SrO	21.82	1.2	*included in "Others1"*	
TiO_2	0.36	0.02	*included in "Others2"*	
Tl_2O	0.91	0.05	*not included in the matrix*	
ZnO	21.82	1.2	*independent variable*	
Subtotal	100.0	5.5	100.0	2.09

[1] Nd_2O_3 is also included in "Others1".

Table 2.4. Glass Property Constraints for Non-Spinel and Spinel Test Matrices.

Property	Non-Spinel Matrix		Spinel Matrix	
	Lower Limit	**Upper Limit**	**Lower Limit**	**Upper Limit**
Viscosity at 1150 °C (η_{1150})[1]	10 P	100 P	10 P	100 P
Conductivity at 1150 °C (σ_{1150})[2]	0.2 S/cm	0.6 S/cm	0.2 S/cm	0.7 S/cm
7-day Normalized B PCT (r_B^{PCT})[3]	*none*	16.695 g/l	*none*	*none*
TCLP Normalized B[4]	*none*	0.3 g/l	*none*	*none*
$T_{1\%}$ for Spinel[5]	*none*	850°C	650°C	1200°C
Liquidus Temperature of ZrO_2 (T_{LZ})[6]	800°C (outer layer) 850°C (inner layer)	1200°C (outer layer) 1150°C (inner layer)	*none*	1420°C(outer layer) *none* (inner layer)
Liquidus Temperature of Thorium-Related Phases)	*none*	*none*	*none*	*none*
Alkali Content (Na_2O + 2 Li_2O) (wt%)	*none*	24.0 (outer layer) 22.5 (inner layer)	*none*	*none*

[1]Property calculated using Model 16 (Table 8) in Reference [8].
[2]Property calculated using Model 1 (Table 10) in Reference [8].
[3]Property calculated using Model of ln[PCT-B (g/l)] with 18 variables (Table 13) in Reference [13].
[4]Property calculated using Model I-(1) in Appendix A-1 in Reference [12].
[5]Property calculated using Model 1 (Table 9) in Reference [11].
[6]Property calculated using Model Z (Table II) for baddeleyite in Reference [15].

Table 2.5. Target Glass Compositions (wt%) for the Non-Spinel Test Matrix.

Glass ID	Point Type[1]	Melt Order	Al_2O_3	B_2O_3	Cr_2O_3	Fe_2O_3	Li_2O	Na_2O	SiO_2	ThO_2	UO_3	ZrO_2	Others	Constant
HLW05-01	I	7	6.000	12.000	0.100	6.060	3.000	8.000	43.770	4.500	4.500	6.080	0.500	5.500
HLW05-02	I	29	10.000	12.000	0.200	5.000	3.000	11.680	41.120	3.000	2.500	5.000	1.000	5.500
HLW05-03	I	11	6.000	11.300	0.200	5.000	3.000	16.000	38.000	3.000	4.500	7.000	0.500	5.500
HLW05-04	I	28	6.000	7.000	0.100	5.000	5.000	10.750	44.000	3.000	4.500	8.150	1.000	5.500
HLW05-05	I	27	6.000	7.000	0.100	7.000	3.250	16.000	44.000	3.000	2.650	5.000	0.500	5.500
HLW05-06	I	2	6.000	7.060	0.200	8.000	3.000	16.000	38.000	4.500	2.500	8.240	1.000	5.500
HLW05-07	Rep-02	1	10.000	12.000	0.200	5.000	3.000	11.680	41.120	3.000	2.500	5.000	1.000	5.500
HLW05-08	I	30	6.000	12.000	0.100	5.000	5.000	11.900	38.000	3.000	2.500	10.500	0.500	5.500
HLW05-09	I	26	6.000	12.000	0.100	7.670	5.000	12.500	38.230	4.500	2.500	5.000	1.000	5.500
HLW05-10	I	18	10.000	7.000	0.200	5.000	5.000	12.500	42.300	4.500	2.500	5.000	0.500	5.500
HLW05-11	I	5	6.000	12.000	0.200	8.000	5.000	8.300	44.000	3.000	2.500	5.000	0.500	5.500
HLW05-12	Rep-06	23	6.000	7.060	0.200	8.000	3.000	16.000	38.000	4.500	2.500	8.240	1.000	5.500
HLW05-13	I	13	9.770	7.000	0.100	7.630	3.000	16.000	38.000	3.000	4.500	5.000	0.500	5.500
HLW05-14	I	15	6.000	11.300	0.200	8.000	5.000	12.500	38.000	3.000	4.500	5.000	1.000	5.500
HLW05-15	O	8	2.000	4.500	0.250	12.000	0.000	16.670	49.000	1.500	4.380	4.000	0.200	5.500
HLW05-16	O	9	5.110	14.000	0.250	1.500	6.000	7.420	36.130	6.000	6.500	11.390	0.200	5.500
HLW05-17	O	22	11.870	14.000	0.050	7.180	6.000	10.750	34.000	1.500	1.000	7.950	0.200	5.500
HLW05-18	O	25	2.000	14.000	0.050	6.460	0.000	11.420	42.030	6.000	1.000	9.540	2.000	5.500
HLW05-19	O	20	13.000	4.500	0.050	5.920	1.450	20.000	34.380	6.000	6.500	2.500	0.200	5.500
HLW05-20	O	24	13.000	14.000	0.250	1.500	0.000	20.000	37.750	1.500	1.000	3.500	2.000	5.500
HLW05-21	O	14	2.000	14.000	0.250	12.000	0.000	19.710	34.000	6.000	1.000	5.340	0.200	5.500
HLW05-22	O	16	13.000	14.000	0.050	2.500	3.700	6.500	44.050	1.500	6.500	2.500	0.200	5.500
HLW05-23	O	3	12.730	4.500	0.250	1.500	6.000	10.000	46.750	6.000	1.000	3.770	2.000	5.500
HLW05-24	O	4	2.170	4.500	0.250	8.940	1.490	20.000	35.640	1.500	6.500	11.500	2.000	5.500
HLW05-25	O	17	2.000	7.430	0.250	9.120	6.000	6.500	49.000	1.500	1.000	11.500	0.200	5.500
HLW05-26	O	6	5.000	4.500	0.050	1.500	1.780	20.000	47.470	1.500	1.000	11.500	0.200	5.500
HLW05-27	O	21	2.000	4.500	0.050	12.000	5.950	10.390	45.610	1.500	6.500	4.000	2.000	5.500
HLW05-28	Rep-18	10	2.000	14.000	0.050	6.460	0.000	11.420	42.030	6.000	1.000	9.540	2.000	5.500
HLW05-29	Rep-26	12	5.000	4.500	0.050	1.500	1.780	20.000	47.470	1.500	1.000	11.500	0.200	5.500
HLW05-30	C	19	6.610	9.860	0.140	6.250	2.780	14.710	40.960	3.200	3.000	6.000	0.980	5.500

[1] I = Inner Layer, O = Outer Layer, C = Center Point, and Replicates are denoted by "Rep-**", where "**" represents a specific Glass ID number for a replicated glass.

Table 2.6. Composition (wt%) Expansions of "Others" and Constant Components for the Non-Spinel Test Matrix.

Glass ID	"Others" Components			Constant Components																	
	CdO	MnO	NiO	Ag_2O	BaO	Bi_2O_3	CaO	F	K_2O	La_2O_3	MgO	P_2O_5	PbO	PdO	Rh_2O_3	RuO_2	SO_3	SrO	TiO_2	Tl_2O	ZnO
HLW05-01	0.125	0.250	0.125	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-02	0.250	0.500	0.250	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-03	0.125	0.250	0.125	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-04	0.250	0.500	0.250	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-05	0.125	0.250	0.125	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-06	0.250	0.500	0.250	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-07	0.250	0.500	0.250	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-08	0.125	0.250	0.125	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-09	0.250	0.500	0.250	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-10	0.125	0.250	0.125	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-11	0.125	0.250	0.125	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-12	0.250	0.500	0.250	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-13	0.125	0.250	0.125	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-14	0.250	0.500	0.250	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-15	0.050	0.100	0.050	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-16	0.050	0.100	0.050	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-17	0.050	0.100	0.050	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-18	0.500	1.000	0.500	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-19	0.050	0.100	0.050	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-20	0.500	1.000	0.500	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-21	0.050	0.100	0.050	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-22	0.050	0.100	0.050	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-23	0.500	1.000	0.500	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-24	0.500	1.000	0.500	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-25	0.050	0.100	0.050	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-26	0.050	0.100	0.050	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-27	0.500	1.000	0.500	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-28	0.500	1.000	0.500	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-29	0.050	0.100	0.050	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200
HLW05-30	0.245	0.490	0.245	0.100	0.500	0.200	0.750	0.050	0.200	0.500	0.100	0.300	0.150	0.020	0.040	0.020	0.100	1.200	0.020	0.050	1.200

Table 2.7 Adjustments of Target Compositions of Initial, Augmentation, and Non-Spinel Matrix Glasses (as augmentation basis for outer layer of HLW06).

Groups of IHLW Glasses	Number of Glasses	Regrouping	Renormalization	Distortion Due to Adjustment
Initial Matrix (HLW02- series)	57	"Others1" and "Others2"	For a constant of 2.09 wt%	Proportion of components in "Others1," "Others2," and "Constant"
Augmentation Matrix (HLW03- series)	45	"Others1" and "Others2"	For a constant of 2.09 wt%	Proportion of components in "Others1," "Others2," and "Constant"
Non-Spinel Matrix (HLW05- series)	30	"Others1" and "Others2"	For a constant of 2.09 wt%	Proportion of components in "Others1," "Others2," and "Constant"
Spinel Matrix (HLW06- series)	20 (Inner Layer Glasses)	Not Needed	Not Needed	None

Table 2.8. Target Glass Compositions (wt%) for the Spinel Test Matrix.

Glass ID	Point Type[1]	Melt Order	Al_2O_3	B_2O_3	Cr_2O_3	Fe_2O_3	Li_2O	MnO	Na_2O	NiO	SiO_2	ThO_2	UO_3	ZnO	ZrO_2	Others1	Others2	Constant
HLW06-01	I	1	11.000	6.500	0.500	7.000	3.000	1.000	14.000	1.000	40.000	1.500	0.750	2.140	1.500	2.000	6.020	2.090
HLW06-02	I	23	10.390	11.000	0.250	7.000	0.250	1.000	20.000	1.000	35.000	0.250	0.750	1.500	1.500	2.000	6.020	2.090
HLW06-03	I	12	11.000	6.500	0.250	14.000	0.250	1.000	14.000	0.600	35.000	0.250	0.750	1.500	4.000	6.000	2.810	2.090
HLW06-04	I	31	8.000	6.500	0.250	7.000	0.250	1.000	20.000	0.600	35.000	1.500	0.750	2.500	4.000	6.000	4.560	2.090
HLW06-05	I	25	8.000	6.500	0.250	7.000	0.250	4.000	20.000	0.600	40.000	1.500	0.750	1.500	1.500	2.000	4.060	2.090
HLW06-06	I	20	11.000	6.500	0.500	7.000	0.250	4.000	14.000	1.000	35.000	1.500	4.000	1.500	4.000	2.000	5.660	2.090
HLW06-07	I	14	8.000	6.500	0.250	14.000	0.250	4.000	15.890	1.000	35.000	0.250	0.750	2.500	1.500	2.000	6.020	2.090
HLW06-08	I	34	8.000	6.500	0.250	7.000	0.250	4.000	14.000	1.000	40.000	0.250	4.000	1.500	1.500	6.000	3.660	2.090
HLW06-09	I	32	8.000	6.500	0.250	14.000	3.000	2.410	14.000	1.000	35.000	0.250	4.000	2.500	4.000	2.000	1.000	2.090
HLW06-10	I	30	8.000	11.000	0.500	7.000	0.250	1.000	14.000	0.600	40.000	0.250	4.000	2.500	4.000	2.000	2.810	2.090
HLW06-11	I	11	8.000	11.000	0.250	14.000	0.250	1.000	14.000	0.600	35.000	1.500	4.000	1.500	1.500	2.000	3.310	2.090
HLW06-12	I	33	9.410	11.000	0.250	7.000	3.000	4.000	14.000	1.000	35.000	1.500	0.750	2.500	1.500	6.000	1.000	2.090
HLW06-13	Rep-06	29	11.000	6.500	0.500	7.000	0.250	4.000	14.000	1.000	35.000	1.500	4.000	1.500	4.000	2.000	5.660	2.090
HLW06-14	I	21	8.000	11.000	0.250	7.000	3.000	4.000	14.000	0.600	35.000	1.500	0.750	1.500	3.290	2.000	6.020	2.090
HLW06-15	I	13	8.000	11.000	0.500	7.000	3.000	2.910	20.000	1.000	35.000	0.250	0.750	1.500	4.000	2.000	1.000	2.090
HLW06-16	I	4	10.000	6.500	0.250	7.000	3.000	1.750	20.000	1.000	35.000	1.500	4.000	2.500	1.500	2.000	1.910	2.090
HLW06-17	Rep-01	6	11.000	6.500	0.500	7.000	3.000	1.000	14.000	1.000	40.000	1.500	0.750	2.140	1.500	2.000	6.020	2.090
HLW06-18	I	16	11.000	11.000	0.250	7.000	0.250	1.000	14.000	1.000	40.000	1.500	0.750	2.500	4.000	2.000	1.660	2.090
HLW06-19	I	8	11.000	6.500	0.500	12.060	0.250	4.000	20.000	0.600	35.000	0.250	0.750	2.500	1.500	2.000	1.000	2.090
HLW06-20	I	9	11.000	6.500	0.250	7.290	3.000	4.000	14.000	0.600	35.000	0.250	4.000	2.500	1.500	2.000	6.020	2.090
HLW06-21	O	35	13.000	4.300	0.000	1.400	0.000	8.000	20.000	0.000	38.770	5.940	6.500	0.000	0.000	0.000	0.000	2.090
HLW06-22	O	18	13.000	15.000	0.600	1.400	6.010	0.000	6.840	0.000	34.560	0.000	6.500	0.000	0.000	14.000	0.000	2.090
HLW06-23	O	7	1.880	4.300	0.600	15.000	0.000	0.000	20.000	0.000	34.690	5.940	0.000	4.000	11.500	0.000	0.000	2.090
HLW06-24	O	2	13.000	4.300	0.000	1.400	0.000	0.000	16.250	0.000	33.000	5.940	0.000	4.000	0.000	14.000	6.020	2.090
HLW06-25	O	3	13.000	15.000	0.600	1.400	6.010	0.000	3.700	0.000	42.240	5.940	0.000	4.000	0.000	0.000	6.020	2.090
HLW06-26	O	17	1.880	4.300	0.600	1.400	0.000	0.730	20.000	0.000	33.000	0.000	6.500	4.000	11.500	14.000	0.000	2.090
HLW06-27	O	22	1.880	9.820	0.000	1.400	6.010	0.000	3.700	0.000	53.100	0.000	6.500	4.000	11.500	0.000	0.000	2.090
HLW06-28	O	24	1.880	15.000	0.600	11.480	6.010	0.000	3.700	0.000	42.720	0.000	6.500	4.000	0.000	0.000	6.020	2.090
HLW06-29	O	26	1.880	4.300	0.000	15.000	6.010	0.000	3.700	0.000	43.560	5.940	0.000	0.000	11.500	0.000	6.020	2.090
HLW06-30	O	27	13.000	4.300	0.000	15.000	0.000	0.000	20.000	0.000	35.110	0.000	6.500	4.000	0.000	0.000	0.000	2.090
HLW06-31	O	10	13.000	4.300	0.600	15.000	5.490	0.000	3.700	0.000	35.880	5.940	0.000	0.000	0.000	14.000	0.000	2.090
HLW06-32	O	28	1.880	15.000	0.600	15.000	0.000	8.000	20.000	0.000	37.430	0.000	0.000	0.000	0.000	0.000	0.000	2.090
HLW06-33	O	19	1.880	4.300	0.000	15.000	4.730	0.000	3.700	0.000	33.000	0.000	6.500	0.000	8.780	14.000	6.020	2.090
HLW06-34	O	15	1.880	15.000	0.600	1.400	0.000	8.000	20.000	0.000	33.030	0.000	6.500	0.000	11.500	0.000	0.000	2.090
HLW06-35	C	5	7.470	10.190	0.300	10.630	3.280	0.290	11.910	0.000	39.430	3.250	3.290	0.310	4.810	1.810	0.940	2.090

[1]I = Inner Layer, O = Outer Layer, C = Center Point, and Replicates are denoted by "Rep-**", where "**" represents a specific Glass ID number for a replicated glass.

Table 2.9. Composition (wt%) Expansions of "Others1," "Others2," and Constant Components for the Spinel Test Matrix.

Glass ID	"Others1" Components					"Others2" Components						Constant Components							
	CdO	La_2O_3	Nd_2O_3[1]	SO_3	SrO	BaO	CaO	K_2O	MgO	PbO	TiO_2	Ag_2O	Bi_2O_3	Cl	F	P_2O_5	PdO	Rh_2O_3	RuO_2
HLW06-01	0.235	0.176	0.329	0.040	1.470	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-02	0.235	0.176	0.329	0.040	1.470	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-03	0.706	0.529	0.487	0.120	4.409	0.140	0.467	0.766	0.546	0.425	0.467	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-04	0.706	0.529	0.487	0.120	4.409	0.227	0.757	1.242	0.886	0.689	0.757	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-05	0.235	0.176	0.329	0.040	1.470	0.202	0.674	1.106	0.789	0.614	0.674	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-06	0.235	0.176	0.329	0.040	1.470	0.282	0.940	1.542	1.100	0.856	0.940	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-07	0.235	0.176	0.329	0.040	1.470	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-08	0.706	0.529	0.487	0.120	4.409	0.182	0.608	0.997	0.711	0.553	0.608	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-09	0.235	0.176	0.329	0.040	1.470	0.050	0.166	0.272	0.194	0.151	0.166	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-10	0.235	0.176	0.329	0.040	1.470	0.140	0.467	0.766	0.546	0.425	0.467	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-11	0.235	0.176	0.329	0.040	1.470	0.165	0.550	0.902	0.643	0.500	0.550	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-12	0.706	0.529	0.487	0.120	4.409	0.050	0.166	0.272	0.194	0.151	0.166	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-13	0.235	0.176	0.329	0.040	1.470	0.282	0.940	1.542	1.100	0.856	0.940	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-14	0.235	0.176	0.329	0.040	1.470	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-15	0.235	0.176	0.329	0.040	1.470	0.050	0.166	0.272	0.194	0.151	0.166	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-16	0.235	0.176	0.329	0.040	1.470	0.095	0.317	0.520	0.371	0.289	0.317	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-17	0.235	0.176	0.329	0.040	1.470	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-18	0.235	0.176	0.329	0.040	1.470	0.083	0.276	0.452	0.323	0.251	0.276	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-19	0.235	0.176	0.329	0.040	1.470	0.050	0.166	0.272	0.194	0.151	0.166	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-20	0.235	0.176	0.329	0.040	1.470	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-21	0.000	0.000	0.250	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-22	1.646	1.234	0.802	0.280	10.287	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-23	0.000	0.000	0.250	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-24	1.646	1.234	0.802	0.280	10.287	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-25	0.000	0.000	0.250	0.000	0.000	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-26	1.646	1.234	0.802	0.280	10.287	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-27	0.000	0.000	0.250	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-28	0.000	0.000	0.250	0.000	0.000	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-29	0.000	0.000	0.250	0.000	0.000	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-30	0.000	0.000	0.250	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-31	1.646	1.234	0.802	0.280	10.287	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-32	0.000	0.000	0.250	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-33	1.646	1.234	0.802	0.280	10.287	0.300	1.000	1.640	1.170	0.910	1.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-34	0.000	0.000	0.250	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130
HLW06-35	0.213	0.160	0.321	0.036	1.330	0.047	0.156	0.256	0.183	0.142	0.156	0.100	0.300	0.200	0.440	0.500	0.120	0.050	0.130

[1]Total concentrations of Nd_2O_3 are listed and include contributions from two groups: "Others1" and Constants (0.250 wt%).

Table 4.1 Compositional Analysis (wt%) of Non-Spinel Matrix Glasses by XRF.

Oxide	HLW05-01	HLW05-02	HLW05-03	HLW05-04	HLW05-05	HLW05-06
Ag_2O	0.09%	0.09%	0.07%	0.10%	0.09%	0.09%
Al_2O_3	6.07%	9.83%	6.21%	5.96%	6.15%	6.35%
B_2O_3	**12.00%**[1]	**12.00%**	**11.30%**	**7.00%**	**7.00%**	**7.06%**
BaO	0.56%	0.50%	0.19%	0.58%	0.59%	0.55%
Bi_2O_3	0.22%	0.21%	0.22%	0.22%	0.21%	0.22%
CaO	0.78%	0.74%	0.81%	0.78%	0.75%	0.76%
CdO	0.13%	0.25%	0.09%	0.29%	0.12%	0.26%
CoO	—[2]	0.00%	—	—	—	—
Cr_2O_3	0.11%	0.21%	0.22%	0.11%	0.11%	0.21%
CuO	0.01%	—	—	—	—	—
Er_2O_3	—	—	0.01%	—	—	—
F	—	—	—	—	—	—
Fe_2O_3	6.39%	4.97%	5.17%	5.33%	7.15%	7.99%
HfO_2	0.13%	0.11%	0.17%	0.18%	0.11%	0.18%
K_2O	0.27%	0.26%	0.29%	0.27%	0.27%	0.26%
La_2O_3	0.50%	0.47%	0.52%	0.50%	0.47%	0.50%
Li_2O	**3.00%**	**3.00%**	**3.00%**	**5.00%**	**3.25%**	**3.00%**
MgO	—	0.08%	0.09%	0.09%	0.10%	0.07%
MnO	0.27%	0.52%	0.27%	0.57%	0.27%	0.52%
MoO_3	—	—	0.49%	—	—	—
Na_2O	8.58%	12.44%	16.22%	10.68%	16.73%	16.64%
NiO	0.13%	0.25%	0.13%	0.27%	0.12%	0.25%
P_2O_5	0.27%	0.28%	0.31%	0.27%	0.28%	0.29%
PbO	0.15%	0.12%	0.13%	0.14%	0.13%	0.13%
PdO	—	—	—	—	—	—
Rh_2O_3	0.05%	0.04%	0.12%	0.05%	0.03%	0.04%
RuO_2	—	—	0.03%	—	—	—
SO_3	0.08%	0.08%	0.10%	0.08%	0.08%	0.10%
SeO_2	0.00%[3]	—	—	0.00%	—	—
SiO_2	43.06%	41.48%	38.43%	42.79%	43.20%	38.05%
Sm_2O_3	—	—	—	—	—	—
SnO_2	0.01%	—	—	—	—	—
SrO	1.40%	1.28%	1.33%	1.40%	1.35%	1.32%
Tb_4O_7	—	—	—	—	—	—
ThO_2	3.88%	2.50%	2.54%	2.74%	2.68%	3.77%
TiO_2	0.04%	0.04%	0.05%	0.04%	0.04%	0.04%
Tl_2O	0.13%	0.10%	0.09%	0.11%	0.10%	0.08%
UO_3	3.91%	2.07%	3.15%	4.47%	2.26%	1.88%
Y_2O_3	—	—	—	—	—	—
ZnO	1.13%	1.05%	1.09%	1.14%	1.09%	1.07%
ZrO_2	6.48%	4.90%	7.07%	8.70%	5.18%	8.23%
TOTAL	99.8%	99.9%	99.9%	99.9%	99.9%	99.9%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.1 Compositional Analysis (wt%) of Non-Spinel Matrix Glasses by XRF (continued).

Oxide	HLW05-07	HLW05-08	HLW05-09	HLW05-10	HLW05-11	HLW05-12
Ag_2O	0.10%	0.10%	0.09%	0.09%	0.08%	0.09%
Al_2O_3	10.02%	6.19%	6.30%	9.90%	6.46%	6.19%
B_2O_3	**12.00%**[1]	**12.00%**	**12.00%**	**7.00%**	**12.00%**	**7.06%**
BaO	0.55%	0.53%	0.48%	0.49%	0.47%	0.52%
Bi_2O_3	0.20%	0.23%	0.22%	0.21%	0.20%	0.22%
CaO	0.73%	0.77%	0.78%	0.77%	0.74%	0.75%
CdO	0.24%	0.13%	0.24%	0.12%	0.12%	0.27%
CoO	0.00%[3]	—	—	—	—	0.00%
Cr_2O_3	0.21%	0.11%	0.12%	0.22%	0.22%	0.22%
CuO	0.00%	—	—	—	—	0.01%
Er_2O_3	—[2]	—	0.01%	—	0.01%	—
F	—	—	—	—	—	—
Fe_2O_3	4.98%	5.21%	8.02%	5.25%	7.94%	8.14%
HfO_2	0.11%	0.24%	0.12%	0.11%	0.11%	0.19%
K_2O	0.28%	0.29%	0.28%	0.28%	0.31%	0.28%
La_2O_3	0.47%	0.52%	0.52%	0.49%	0.47%	0.53%
Li_2O	**3.00%**	**5.00%**	**5.00%**	**5.00%**	**5.00%**	**3.00%**
MgO	0.06%	0.06%	0.13%	0.09%	0.12%	0.07%
MnO	0.51%	0.28%	0.55%	0.27%	0.26%	0.54%
MoO_3	—	—	—	—	—	—
Na_2O	12.21%	11.71%	13.21%	13.04%	8.20%	16.39%
NiO	0.25%	0.14%	0.27%	0.13%	0.13%	0.26%
P_2O_5	0.29%	0.29%	0.28%	0.29%	0.27%	0.28%
PbO	0.12%	0.13%	0.17%	0.13%	0.13%	0.13%
PdO	—	—	—	—	—	—
Rh_2O_3	0.04%	0.03%	0.02%	0.03%	0.03%	0.04%
RuO_2	—	—	—	—	—	—
SO_3	0.08%	0.08%	0.08%	0.08%	0.08%	0.08%
SeO_2	—	—	—	—	—	0.00%
SiO_2	41.90%	37.83%	39.06%	42.57%	44.14%	38.19%
Sm_2O_3	—	—	—	—	—	—
SnO_2	—	0.01%	0.01%	—	—	—
SrO	1.25%	1.35%	1.35%	1.34%	1.24%	1.33%
Tb_4O_7	—	—	—	—	—	—
ThO_2	2.47%	2.62%	2.66%	3.82%	2.65%	3.81%
TiO_2	0.04%	0.05%	0.04%	0.04%	0.04%	0.04%
Tl_2O	0.09%	0.10%	0.09%	0.11%	0.10%	0.10%
UO_3	1.80%	2.11%	1.54%	1.86%	2.62%	1.76%
Y_2O_3	—	0.01%	—	—	—	0.01%
ZnO	1.04%	1.12%	1.12%	1.11%	1.05%	1.09%
ZrO_2	4.92%	10.70%	5.20%	5.09%	4.83%	8.32%
TOTAL	100.0%	99.9%	100.0%	99.9%	99.8%	99.9%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.1 Compositional Analysis (wt%) of Non-Spinel Matrix Glasses by XRF (continued).

Oxide	HLW05-13	HLW05-14	HLW05-15	HLW05-16	HLW05-17	HLW05-18
Ag_2O	0.10%	0.08%	0.10%	0.09%	0.08%	0.09%
Al_2O_3	9.16%	6.05%	2.74%	5.44%	11.57%	2.59%
B_2O_3	**7.00%**[1]	**11.30%**	**4.50%**	**14.00%**	**14.00%**	**14.00%**
BaO	0.22%	0.21%	0.56%	0.55%	0.45%	0.51%
Bi_2O_3	0.24%	0.21%	0.20%	0.22%	0.21%	0.22%
CaO	0.83%	0.81%	0.76%	0.80%	0.75%	0.76%
CdO	0.11%	0.20%	0.04%	0.04%	0.04%	0.55%
CoO	0.00%[3]	0.00%	0.00%	—	0.00%	—
Cr_2O_3	0.12%	0.22%	0.27%	0.29%	0.06%	0.06%
CuO	—[2]	—	0.01%	—	—	0.01%
Er_2O_3	—	—	—	—	0.01%	—
F	—	—	—	—	—	—
Fe_2O_3	8.45%	8.20%	11.90%	1.68%	7.12%	6.74%
HfO_2	0.13%	0.12%	0.09%	0.28%	0.17%	0.21%
K_2O	0.29%	0.28%	0.27%	0.26%	0.29%	0.26%
La_2O_3	0.55%	0.51%	0.49%	0.53%	0.51%	0.54%
Li_2O	**3.00%**	**5.00%**	**0.00%**	**6.00%**	**6.00%**	**0.00%**
MgO	0.07%	0.08%	0.08%	0.07%	0.07%	0.10%
MnO	0.29%	0.54%	0.11%	0.11%	0.11%	1.09%
MoO_3	0.71%	0.57%	—	—	—	—
Na_2O	15.48%	13.18%	17.62%	6.95%	11.95%	11.46%
NiO	0.15%	0.26%	0.05%	0.06%	0.05%	0.53%
P_2O_5	0.28%	0.30%	0.31%	0.29%	0.28%	0.28%
PbO	0.15%	0.14%	0.13%	0.15%	0.12%	0.13%
PdO	—	—	—	—	—	—
Rh_2O_3	0.18%	0.15%	0.04%	—	0.02%	0.02%
RuO_2	0.02%	0.02%	—	—	—	—
SO_3	0.08%	0.08%	0.09%	0.06%	0.07%	0.08%
SeO_2	—	—	—	—	0.00%	0.00%
SiO_2	36.43%	37.36%	48.52%	36.10%	34.45%	40.67%
Sm_2O_3	—	—	0.01%	—	—	—
SnO_2	—	—	—	—	—	—
SrO	1.52%	1.37%	1.31%	1.43%	1.24%	1.38%
Tb_4O_7	—	—	—	—	—	—
ThO_2	2.92%	2.59%	1.25%	5.12%	1.20%	5.42%
TiO_2	0.05%	0.05%	0.04%	0.05%	0.04%	0.05%
Tl_2O	0.11%	0.10%	0.10%	0.11%	0.07%	0.11%
UO_3	4.21%	3.63%	3.13%	5.84%	0.83%	0.77%
Y_2O_3	—	—	—	0.01%	0.01%	0.01%
ZnO	1.20%	1.10%	1.08%	1.14%	1.05%	1.12%
ZrO_2	5.86%	5.22%	4.10%	12.20%	7.06%	10.13%
TOTAL	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.1 Compositional Analysis (wt%) of Non-Spinel Matrix Glasses by XRF (continued).

Oxide	HLW05-19	HLW05-20	HLW05-21	HLW05-22	HLW05-23	HLW05-24
Ag_2O	0.10%	0.10%	0.07%	0.08%	0.10%	0.08%
Al_2O_3	12.76%	12.34%	2.54%	12.87%	12.39%	2.44%
B_2O_3	**4.50%**[1]	**14.00%**	**14.00%**	**14.00%**	**4.50%**	**4.50%**
BaO	0.59%	0.52%	0.21%	0.49%	0.55%	0.54%
Bi_2O_3	0.24%	0.21%	0.21%	0.22%	0.22%	0.22%
CaO	0.82%	0.77%	0.75%	0.77%	0.79%	0.77%
CdO	0.05%	0.53%	0.02%	0.04%	0.53%	0.51%
CoO	—[2]	—	—	—	—	0.01%
Cr_2O_3	0.06%	0.28%	0.27%	0.06%	0.28%	0.28%
CuO	—	0.00%[3]	—	—	—	—
Er_2O_3	—	—	0.01%	—	—	0.01%
F	—	—	—	—	—	—
Fe_2O_3	6.62%	1.64%	11.89%	2.60%	1.66%	9.07%
HfO_2	0.05%	0.08%	0.13%	0.05%	0.08%	0.28%
K_2O	0.26%	0.26%	0.27%	0.29%	0.29%	0.25%
La_2O_3	0.55%	0.53%	0.51%	0.49%	0.51%	0.52%
Li_2O	**1.45%**	**0.00%**	**0.00%**	**3.70%**	**6.00%**	**1.49%**
MgO	0.09%	0.11%	0.08%	0.09%	0.08%	0.07%
MnO	0.11%	1.07%	0.10%	0.10%	1.09%	1.06%
MoO_3	—	—	0.22%	—	—	—
Na_2O	20.34%	20.36%	20.21%	6.79%	10.36%	20.16%
NiO	0.06%	0.54%	0.05%	0.05%	0.53%	0.52%
P_2O_5	0.25%	0.28%	0.30%	0.29%	0.30%	0.27%
PbO	0.14%	0.13%	0.12%	0.14%	0.13%	0.14%
PdO	—	—	—	—	—	—
Rh_2O_3	—	0.02%	0.06%	0.05%	0.02%	—
RuO_2	—	—	0.06%	—	—	—
SO_3	0.07%	0.08%	0.07%	0.09%	0.09%	0.10%
SeO_2	—	—	—	—	—	0.01%
SiO_2	33.68%	37.55%	33.62%	44.75%	46.79%	34.96%
Sm_2O_3	—	—	—	—	—	—
SnO_2	—	—	0.01%	—	—	—
SrO	1.49%	1.35%	1.33%	1.33%	1.39%	1.35%
Tb_4O_7	0.01%	—	—	—	—	—
ThO_2	5.62%	1.31%	5.14%	1.22%	5.21%	1.30%
TiO_2	0.06%	0.04%	0.05%	0.04%	0.04%	0.04%
Tl_2O	0.09%	0.10%	0.10%	0.11%	0.11%	0.08%
UO_3	5.79%	0.90%	0.94%	5.55%	0.72%	5.76%
Y_2O_3	—	0.00%	0.01%	—	0.01%	—
ZnO	1.20%	1.12%	1.07%	1.08%	1.12%	1.10%
ZrO_2	2.84%	3.67%	5.48%	2.51%	4.03%	12.01%
TOTAL	99.9%	99.9%	99.9%	99.8%	99.9%	99.9%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.1 Compositional Analysis (wt%) of Non-Spinel Matrix Glasses by XRF (continued).

Oxide	HLW05-25	HLW05-26	HLW05-27	HLW05-28	HLW05-29	HLW05-30
Ag_2O	0.11%	0.12%	0.10%	0.07%	0.11%	0.09%
Al_2O_3	2.81%	5.07%	2.87%	2.57%	5.36%	6.83%
B_2O_3	**7.43%**[1]	**4.50%**	**4.50%**	**14.00%**	**4.50%**	**9.86%**
BaO	0.52%	0.59%	0.49%	0.20%	0.20%	0.52%
Bi_2O_3	0.21%	0.22%	0.23%	0.22%	0.23%	0.21%
CaO	0.76%	0.79%	0.78%	0.77%	0.81%	0.74%
CdO	0.05%	0.06%	0.49%	0.40%	0.05%	0.25%
CoO	—[2]	—	0.01%	—	—	—
Cr_2O_3	0.27%	0.06%	0.06%	0.06%	0.06%	0.16%
CuO	—	—	—	—	—	0.00%
Er_2O_3	0.01%	—	0.01%	0.01%	—	—
F	—	—	—	—	—	—
Fe_2O_3	9.08%	1.66%	12.28%	6.49%	1.64%	6.30%
HfO_2	0.24%	0.26%	0.09%	0.22%	0.27%	0.13%
K_2O	0.30%	0.29%	0.31%	0.32%	0.33%	0.28%
La_2O_3	0.49%	0.52%	0.48%	0.51%	0.54%	0.47%
Li_2O	**6.00%**	**1.78%**	**5.95%**	**0.00%**	**1.78%**	**2.78%**
MgO	—	0.08%	0.16%	0.09%	0.10%	0.09%
MnO	0.11%	0.11%	1.07%	1.04%	0.12%	0.51%
MoO_3	—	0.02%	—	0.25%	0.26%	—
Na_2O	6.99%	19.51%	10.42%	11.35%	19.31%	15.54%
NiO	0.05%	0.06%	0.53%	0.51%	0.06%	0.24%
P_2O_5	0.28%	0.28%	0.28%	0.31%	0.30%	0.27%
PbO	0.12%	0.13%	0.13%	0.12%	0.14%	0.13%
PdO	—	—	—	—	—	—
Rh_2O_3	0.05%	0.05%	—	0.06%	0.10%	0.04%
RuO_2	—	—	—	0.05%	0.07%	—
SO_3	0.09%	0.08%	0.09%	0.07%	0.08%	0.08%
SeO_2	—	0.01%	—	—	0.01%	—
SiO_2	48.29%	46.32%	44.85%	41.98%	46.11%	41.23%
Sm_2O_3	—	—	—	—	—	—
SnO_2	0.01%	—	0.01%	—	—	—
SrO	1.26%	1.39%	1.32%	1.32%	1.40%	1.28%
Tb_4O_7	—	—	—	—	—	—
ThO_2	1.22%[1]	1.38%	1.28%	5.09%	1.37%	2.73%
TiO_2	0.05%	0.04%	0.04%	0.05%	0.05%	0.05%
Tl_2O	0.10%	0.10%	0.11%	0.12%	0.10%	0.09%
UO_3	0.77%	0.89%	5.85%	0.86%	0.71%	1.95%
Y_2O_3	—	0.01%	—	0.01%	0.01%	0.00%[3]
ZnO	1.06%	1.13%	1.10%	1.08%	1.13%	1.08%
ZrO_2	11.11%	12.35%	4.02%	9.69%	12.55%	6.06%
TOTAL	99.8%	99.8%	99.9%	99.9%	99.8%	100.0%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.2 Compositional Analysis (wt%) of Spinel Matrix Glasses by XRF.

Oxide	HLW06-01	HLW06-02	HLW06-03	HLW06-04	HLW06-05	HLW06-06
Ag_2O	0.10%	0.11%	0.11%	0.10%	0.11%	0.09%
Al_2O_3	10.69%	10.00%	10.53%	7.77%	7.84%	10.55%
B_2O_3	**6.50%**[1]	**11.00%**	**6.50%**	**6.50%**	**6.50%**	**6.50%**
BaO	0.30%	0.26%	—	—	0.20%	0.29%
Bi_2O_3	0.34%	0.35%	0.33%	0.34%	0.35%	0.34%
CaO	1.05%	1.04%	0.51%	0.79%	0.71%	0.98%
CdO	0.27%	0.24%	0.77%	0.85%	0.25%	0.26%
Ce_2O_3	—[2]	—	—	—	—	—
Cl	0.18%	0.14%	0.17%	0.14%	0.14%	0.17%
CoO	0.00%	0.00%	0.01%	—	0.00%	—
Cr_2O_3	0.56%	0.29%	0.27%	0.29%	0.29%	0.53%
CuO	0.00%[3]	0.00%	0.01%	—	—	0.00%
Er_2O_3	—	0.01%	0.01%		—	—
Fe_2O_3	7.54%	7.49%	14.39%	7.44%	7.44%	7.24%
HfO_2	0.03%	0.03%	0.09%	0.09%	0.05%	0.09%
K_2O	1.73%	1.67%	0.85%	1.25%	1.17%	1.61%
La_2O_3	0.19%	0.19%	0.55%	0.57%	0.18%	0.20%
Li_2O	**3.00%**	**0.25%**	**0.25%**	**0.25%**	**0.25%**	**0.25%**
MgO	1.06%	1.14%	0.48%	0.78%	0.70%	1.01%
MnO	1.12%	1.12%	1.07%	1.09%	4.40%	4.28%
MoO_3	—	—	—	—	—	—
Na_2O	14.22%	20.07%	14.80%	20.28%	20.80%	15.01%
Nd_2O_3	0.37%	0.35%	0.51%	0.50%	0.33%	0.36%
NiO	1.07%	1.09%	0.59%	0.66%	0.66%	1.00%
P_2O_5	0.45%	0.44%	0.42%	0.44%	0.43%	0.44%
PbO	0.88%	0.88%	0.40%	0.67%	0.59%	0.80%
PdO	0.10%	0.10%	0.09%	0.10%	0.10%	0.08%
Pr_2O_3	—	—	—	—	—	—
Rh_2O_3	0.04%	0.04%	0.05%	0.05%	0.04%	0.07%
RuO_2	0.12%	0.11%	0.12%	0.11%	0.12%	0.11%
SO_3	0.04%	0.04%	0.10%	0.10%	0.03%	0.04%
SeO_2	—	—	—	—	—	—
SiO_2	39.43%	34.63%	33.75%	33.71%	38.56%	34.38%
Sm_2O_3	—	—	—	—	—	—
SnO_2	—	0.01%	—	—	—	—
SrO	1.72%	1.69%	4.94%	5.09%	1.72%	1.74%
Tb_4O_7	—	—	—	—	0.01%	—
ThO_2	1.35%	0.24%	0.22%	1.39%	1.43%	1.41%
TiO_2	1.16%	1.15%	0.54%	0.87%	0.76%	1.00%
UO_3	0.62%	0.73%	0.74%	0.71%	0.70%	3.35%
Y_2O_3	0.00%	—	0.00%	—	—	0.00%
ZnO	2.07%	1.44%	1.38%	2.39%	1.45%	1.38%
ZrO_2	1.70%	1.68%	4.31%	4.45%	1.68%	4.38%
TOTAL	100.0%	100.0%	99.9%	99.8%	100.0%	99.9%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.2 Compositional Analysis (wt%) of Spinel Matrix Glasses by XRF (continued).

Oxide	HLW06-07	HLW06-08	HLW06-09	HLW06-10	HLW06-11	HLW06-12
Ag_2O	0.11%	0.11%	0.11%	0.10%	0.10%	0.11%
Al_2O_3	8.00%	7.83%	8.12%	8.05%	7.76%	9.07%
B_2O_3	**6.50%**[1]	**6.50%**	**6.50%**	**11.00%**	**11.00%**	**11.00%**
BaO	0.33%	—	—	0.15%	0.17%	—
Bi_2O_3	0.32%	0.35%	0.31%	0.34%	0.33%	0.35%
CaO	1.00%	0.64%	0.19%	0.49%	0.59%	0.19%
CdO	0.25%	0.82%	0.26%	0.26%	0.26%	0.84%
Ce_2O_3	—[2]	—	—	—	—	—
Cl	0.14%	0.15%	0.16%	0.18%	0.18%	0.13%
CoO	0.01%	0.00%	—	0.00%	0.01%	—
Cr_2O_3	0.26%	0.28%	0.26%	0.51%	0.27%	0.28%
CuO	—	—	—	—	—	—
Er_2O_3	0.01%	—	0.02%	0.01%	0.01%	—
Fe_2O_3	13.97%	7.44%	13.76%	7.24%	14.37%	7.37%
HfO_2	0.03%	0.03%	0.10%	0.09%	0.03%	0.04%
K_2O	1.67%	1.06%	0.37%	0.84%	0.96%	0.36%
La_2O_3	0.18%	0.54%	0.19%	0.19%	0.18%	0.57%
Li_2O	**0.25%**	**0.25%**	**3.00%**	**0.25%**	**0.25%**	**3.00%**
MgO	1.03%	0.67%	0.18%	0.51%	0.59%	0.17%
MnO	4.23%	4.41%	2.52%	1.09%	1.08%	4.38%
MoO_3	—	—	—	—	—	—
Na_2O	17.30%	14.25%	15.19%	14.86%	14.91%	14.18%
Nd_2O_3	0.32%	0.48%	0.36%	0.35%	0.33%	0.49%
NiO	0.96%	1.09%	0.91%	0.62%	0.58%	1.10%
P_2O_5	0.41%	0.41%	0.43%	0.43%	0.43%	0.41%
PbO	0.81%	0.55%	0.15%	0.41%	0.48%	0.15%
PdO	0.10%	0.11%	0.08%	0.08%	0.08%	0.09%
Pr_2O_3	—	—	—	—	—	—
Rh_2O_3	0.04%	0.09%	0.09%	0.07%	0.07%	0.05%
RuO_2	0.11%	0.11%	0.11%	0.11%	0.11%	0.10%
SO_3	0.04%	0.10%	0.05%	0.05%	0.04%	0.09%
SeO_2	—	—	—	—	—	—
SiO_2	34.18%	38.44%	34.74%	39.00%	34.63%	33.96%
Sm_2O_3	0.03%	—	—	—	—	—
SnO_2	—	—	—	—	—	—
SrO	1.61%	5.20%	1.61%	1.68%	1.70%	5.08%
Tb_4O_7	0.01%	—	—	—	—	—
ThO_2	0.22%	0.22%	0.19%	0.21%	1.40%	1.43%
TiO_2	1.11%	0.70%	0.20%	0.53%	0.62%	0.21%
UO_3	0.63%	3.84%	3.44%	3.75%	3.55%	0.71%
Y_2O_3	0.00%[3]	—	0.00%	0.00%	—	—
ZnO	2.26%	1.47%	2.21%	2.30%	1.38%	2.37%
ZrO_2	1.58%	1.69%	4.15%	4.29%	1.58%	1.67%
TOTAL	100.0%	99.8%	99.9%	100.0%	100.0%	99.9%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.2 Compositional Analysis (wt%) of Spinel Matrix Glasses by XRF (continued).

Oxide	HLW06-13	HLW06-14	HLW06-15	HLW06-16	HLW06-17	HLW06-18
Ag_2O	0.09%	0.10%	0.10%	0.11%	0.09%	0.10%
Al_2O_3	10.59%	7.96%	7.90%	9.61%	10.95%	10.65%
B_2O_3	**6.50%**[1]	**11.00%**	**11.00%**	**6.50%**	**6.50%**	**11.00%**
BaO	0.33%	0.34%	—	—	0.27%	—
Bi_2O_3	0.33%	0.35%	0.34%	0.36%	0.34%	0.32%
CaO	0.96%	1.03%	0.19%	0.36%	1.04%	0.31%
CdO	0.27%	0.26%	0.25%	0.27%	0.24%	0.24%
Ce_2O_3	—[2]	—	—	—	—	—
Cl	0.17%	0.11%	0.12%	0.14%	0.16%	0.19%
CoO	—	0.00%[3]	0.00%	—	0.00%	—
Cr_2O_3	0.52%	0.28%	0.56%	0.30%	0.56%	0.26%
CuO	—	—	—	—	—	—
Er_2O_3	—	—	0.01%	0.01%	—	—
Fe_2O_3	7.18%	7.31%	7.40%	7.73%	7.30%	7.22%
HfO_2	0.10%	0.07%	0.09%	0.04%	0.03%	0.09%
K_2O	1.59%	1.68%	0.37%	0.61%	1.73%	0.57%
La_2O_3	0.20%	0.18%	0.19%	0.19%	0.19%	0.20%
Li_2O	**0.25%**	**3.00%**	**3.00%**	**3.00%**	**3.00%**	**0.25%**
MgO	1.01%	1.11%	0.19%	0.30%	1.06%	0.27%
MnO	4.29%	4.39%	3.21%	2.02%	1.09%	1.10%
MoO_3	—	—	—	—	—	—
Na_2O	14.71%	14.07%	20.41%	20.38%	14.54%	14.84%
Nd_2O_3	0.36%	0.34%	0.33%	0.38%	0.36%	0.34%
NiO	0.98%	0.65%	1.09%	1.14%	1.06%	1.01%
P_2O_5	0.43%	0.42%	0.42%	0.44%	0.43%	0.43%
PbO	0.82%	0.87%	0.15%	0.30%	0.86%	0.23%
PdO	0.07%	0.10%	0.08%	0.08%	0.08%	0.08%
Pr_2O_3	—	—	—	—	—	—
Rh_2O_3	0.07%	0.04%	0.03%	0.07%	0.05%	0.05%
RuO_2	0.10%	0.09%	0.06%	0.08%	0.12%	0.12%
SO_3	0.03%	0.03%	0.10%	0.03%	0.04%	0.03%
SeO_2	—	—	0.00%	—	—	0.00%
SiO_2	34.19%	34.14%	33.80%	33.64%	39.37%	39.45%
Sm_2O_3	—	—	—	—	—	—
SnO_2	—	—	—	—	0.01%	0.01%
SrO	1.71%	1.71%	1.68%	1.81%	1.66%	1.63%
Tb_4O_7	—	—	—	—	—	—
ThO_2	1.43%	1.42%	0.22%	1.49%	1.40%	1.36%
TiO_2	1.04%	1.13%	0.21%	0.38%	1.14%	0.33%
UO_3	3.91%	0.73%	0.70%	3.92%	0.68%	0.70%
Y_2O_3	—	—	0.00%	—	—	0.00%
ZnO	1.40%	1.43%	1.45%	2.50%	2.02%	2.32%
ZrO_2	4.37%	3.64%	4.35%	1.74%	1.63%	4.23%
TOTAL	100.0%	100.0%	100.0%	99.9%	100.0%	99.9%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.2 Compositional Analysis (wt%) of Spinel Matrix Glasses by XRF (continued).

Oxide	HLW06-19	HLW06-20	HLW06-21	HLW06-22	HLW06-23	HLW06-24
Ag_2O	0.10%	0.09%	0.09%	0.12%	0.11%	0.11%
Al_2O_3	10.41%	10.56%	12.63%	11.96%	2.60%	11.82%
B_2O_3	**6.50%**[1]	**6.50%**	**4.30%**	**15.00%**	**4.30%**	**4.30%**
BaO	—[2]	0.30%	—	—	—	—
Bi_2O_3	0.33%	0.35%	0.36%	0.38%	0.31%	0.38%
CaO	0.20%	1.05%	0.02%	0.03%	0.03%	1.07%
CdO	0.24%	0.25%	—	2.11%	—	2.11%
Ce_2O_3	—	—	—	—	—	—
Cl	0.15%	0.14%	0.18%	0.11%	0.18%	0.14%
CoO	0.08%	0.01%	—	—	0.01%	—
Cr_2O_3	0.54%	0.27%	—	0.72%	0.68%	—
CuO	—	—	—	—	—	0.01%
Er_2O_3	0.02%	0.01%	—	—	0.01%	—
Fe_2O_3	12.37%	7.62%	1.56%	1.62%	15.73%	1.61%
HfO_2	0.03%	0.03%	—	—	0.26%	—
K_2O	0.35%	1.68%	0.08%	0.07%	0.11%	1.64%
La_2O_3	0.19%	0.20%	—	1.40%	0.02%	1.35%
Li_2O	**0.25%**	**3.00%**	—	**6.01%**	—	—
MgO	0.17%	1.07%	—	—	—	1.05%
MnO	4.28%	4.36%	8.97%	0.01%	0.00%[3]	0.01%
MoO_3	—	—	—	—	—	—
Na_2O	21.32%	15.19%	20.82%	6.42%	20.12%	16.40%
Nd_2O_3	0.33%	0.32%	0.25%	0.84%	0.26%	0.91%
NiO	0.60%	0.62%	0.00%	—	0.00%	—
P_2O_5	0.43%	0.43%	0.44%	0.42%	0.43%	0.42%
PbO	0.10%	0.87%	—	—	—	0.94%
PdO	0.10%	0.08%	0.10%	0.08%	0.10%	0.12%
Pr_2O_3	—	—	—	0.03%	—	0.02%
Rh_2O_3	0.05%	0.06%	0.10%	0.15%	0.06%	0.05%
RuO_2	0.12%	0.08%	0.12%	0.09%	0.13%	0.13%
SO_3	0.04%	0.04%	—	0.19%	—	0.22%
SeO_2	—	—	—	—	—	—
SiO_2	33.90%	34.09%	38.49%	33.00%	33.87%	30.87%
Sm_2O_3	0.02%	—	—	—	—	—
SnO_2	—	—	—	—	—	—
SrO	1.63%	1.70%	0.03%	12.88%	0.02%	12.66%
Tb_4O_7	0.02%	—	—	—	—	—
ThO_2	0.25%	0.23%	5.28%	—	4.95%	6.12%
TiO_2	0.21%	1.12%	0.02%	0.03%	0.03%	1.18%
UO_3	0.68%	3.69%	6.14%	6.20%	—	—
Y_2O_3	—	—	—	—	0.01%	—
ZnO	2.32%	2.36%	0.01%	0.02%	3.76%	3.92%
ZrO_2	1.65%	1.64%	—	0.05%	11.82%	—
TOTAL	100.0%	100.0%	100.0%	99.9%	99.9%	99.5%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.2 Compositional Analysis (wt%) of Spinel Matrix Glasses by XRF (continued).

Oxide	HLW06-25	HLW06-26	HLW06-27	HLW06-28	HLW06-29	HLW06-30
Ag_2O	0.10%	0.11%	0.11%	0.08%	0.09%	0.10%
Al_2O_3	13.10%	1.94%	3.10%	2.63%	3.00%	12.83%
B_2O_3	**15.00%**[1]	**4.30%**	**9.82%**	**15.00%**	**4.30%**	**4.30%**
BaO	0.29%	—	—	0.30%	0.33%	—
Bi_2O_3	0.34%	0.36%	0.32%	0.30%	0.32%	0.33%
CaO	1.03%	0.02%	0.03%	1.00%	1.02%	0.02%
CdO	—[2]	1.96%	—	—	—	—
Ce_2O_3	—	0.02%	—	—	—	—
Cl	0.16%	0.12%	0.15%	0.16%	0.13%	0.19%
CoO	—	—	—	0.00%[3]	—	—
Cr_2O_3	0.65%	0.68%	—	0.58%	—	0.01%
CuO	—	0.00%	—	—	—	—
Er_2O_3	—	—	—	0.01%	—	0.01%
Fe_2O_3	1.52%	1.50%	1.51%	10.92%	14.94%	15.14%
HfO_2	—	0.34%	0.25%	—	0.25%	—
K_2O	1.79%	—	0.18%	1.63%	1.79%	0.08%
La_2O_3	—	1.26%	—	—	—	—
Li_2O	**6.01%**	—	**6.01%**	**6.01%**	**6.01%**	—
MgO	1.08%	—	—	1.09%	1.07%	—
MnO	—	0.79%	0.02%	0.00%	—	0.00%
MoO_3	—	—	—	—	—	—
Na_2O	3.99%	19.03%	4.16%	3.77%	3.89%	22.10%
Nd_2O_3	0.29%	0.78%	0.22%	0.24%	0.25%	0.24%
NiO	—	—	—	—	—	—
P_2O_5	0.44%	0.38%	0.45%	0.44%	0.45%	0.43%
PbO	0.85%	—	0.01%	0.75%	0.80%	0.01%
PdO	0.09%	0.03%	0.18%	0.06%	0.07%	0.09%
Pr_2O_3	—	0.02%	—	—	—	—
Rh_2O_3	0.05%	0.09%	0.13%	0.09%	0.04%	0.09%
RuO_2	0.13%	0.07%	0.13%	0.07%	0.10%	0.11%
SO_3	—	0.21%	—	0.01%	—	0.01%
SeO_2	—	0.01%	—	—	—	—
SiO_2	42.90%	29.37%	52.21%	43.01%	43.75%	35.20%
Sm_2O_3	—	—	—	—	—	0.01%
SnO_2	—	—	—	—	—	—
SrO	0.03%	11.92%	0.03%	0.01%	0.02%	0.01%
Tb_4O_7	—	—	—	0.01%	0.01%	—
ThO_2	5.25%	—	—	—	4.79%	—
TiO_2	1.12%	0.02%	0.04%	1.06%	1.09%	0.02%
UO_3	—	6.25%	5.55%	7.43%	0.01%	5.01%
Y_2O_3	0.01%	—	0.01%	—	0.01%	—
ZnO	3.76%	3.74%	3.60%	3.32%	0.02%	3.62%
ZrO_2	—	14.70%	11.39%	—	11.40%	—
TOTAL	100.0%	100.0%	99.6%	100.0%	100.0%	100.0%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.2 Compositional Analysis (wt%) of Spinel Matrix Glasses by XRF (continued).

Oxide	HLW06-31	HLW06-32	HLW06-33	HLW06-34	HLW06-35
Ag_2O	0.11%	0.12%	0.08%	0.12%	0.10%
Al_2O_3	12.35%	2.35%	2.59%	2.51%	7.36%
B_2O_3	**4.30%**[1]	**15.00%**	**4.30%**	**15.00%**	**10.19%**
BaO	—[2]	—	—	—	—
Bi_2O_3	0.35%	0.37%	0.34%	0.35%	0.34%
CaO	0.03%	0.03%	1.05%	0.02%	0.19%
CdO	1.95%	—	1.87%	—	0.24%
Ce_2O_3	—	—	—	0.02%	—
Cl	0.16%	0.15%	0.05%	0.14%	0.15%
CoO	0.01%	—	0.01%	—	0.01%
Cr_2O_3	0.63%	0.69%	—	0.69%	0.33%
CuO	0.01%	—	—	—	—
Er_2O_3	0.01%	—	0.01%	—	0.01%
Fe_2O_3	15.08%	16.33%	15.15%	1.60%	11.02%
HfO_2	—	—	0.20%	0.29%	0.12%
K_2O	0.08%	0.07%	1.63%	0.09%	0.33%
La_2O_3	1.33%	—	1.27%	—	0.18%
Li_2O	**5.49%**	—	**4.73%**	—	**3.28%**
MgO	—	—	1.03%	—	0.20%
MnO	0.02%	9.14%	—	9.06%	0.31%
MoO_3	—	—	—	0.03%	—
Na_2O	4.19%	19.20%	3.90%	18.79%	12.78%
Nd_2O_3	0.83%	0.29%	0.81%	0.26%	0.37%
NiO	—	—	—	0.00%	—
P_2O_5	0.43%	0.43%	0.41%	0.41%	0.44%
PbO	—	0.00%[3]	0.87%	0.01%	0.13%
PdO	0.10%	0.10%	0.06%	0.13%	0.08%
Pr_2O_3	0.02%	—	—	—	--
Rh_2O_3	0.05%	0.04%	0.08%	0.11%	0.06%
RuO_2	0.13%	0.10%	0.04%	0.13%	0.10%
SO_3	0.22%	0.02%	0.15%	—	0.03%
SeO_2	—	—	—	0.01%	—
SiO_2	34.65%	35.39%	31.29%	31.28%	38.47%
Sm_2O_3	—	—	—	—	—
SnO_2	—	—	—	0.01%	—
SrO	11.75%	0.01%	11.52%	0.02%	1.52%
Tb_4O_7	—	—	—	—	—
ThO_2	5.65%	—	—	—	2.99%
TiO_2	0.03%	0.02%	1.12%	0.02%	0.20%
UO_3	—	—	5.99%	5.86%	2.93%
Y_2O_3	—	—	—	—	—
ZnO	0.01%	—	—	0.02%	0.30%
ZrO_2	—	0.01%	9.08%	13.01%	5.22%
TOTAL	100.0%	99.9%	99.6%	100.0%	100.0%

[1] Target values (in bold) are used for B_2O_3 and Li_2O.
[2] — indicates empty data field.
[3] Analyzed values are rounded to 2 significant figures.

Table 4.3. PCT Release Data for Spinel Matrix Glasses.

	HLW06-01	HLW06-02	HLW06-03	HLW06-04	HLW06-05	HLW06-06	HLW06-07
	Leachate Concentration (ppm)						
B	12.720	67.470	6.470	38.800	15.600	6.530	11.830
Li	7.070	1.123	0.227	0.923	0.623	0.473	0.483
Na	68.500	211.800	51.270	348.100	154.200	48.760	117.400
Si	55.020	57.420	32.260	95.030	76.600	24.170	64.090
	Normalized Leachate Concentration (g/l)						
B	0.630	1.975	0.321	1.922	0.773	0.324	0.586
Li	0.507	0.967	0.195	0.795	0.536	0.407	0.416
Na	0.660	1.427	0.494	2.346	1.039	0.469	0.996
Si	0.294	0.351	0.197	0.581	0.410	0.148	0.392
	Normalized Mass Loss (g/m^2)						
B	0.315	0.988	0.160	0.961	0.386	0.162	0.293
Li	0.254	0.484	0.098	0.397	0.268	0.204	0.208
Na	0.330	0.714	0.247	1.173	0.520	0.235	0.498
Si	0.147	0.175	0.099	0.290	0.205	0.074	0.196
	Normalized Leach Rate ($g/(m^2$-day))						
B	0.045	0.141	0.023	0.137	0.055	0.023	0.042
Li	0.036	0.069	0.014	0.057	0.038	0.029	0.030
Na	0.047	0.102	0.035	0.168	0.074	0.034	0.071
Si	0.021	0.025	0.014	0.041	0.029	0.011	0.028
Leachate pH	11.04	11.18	10.54	11.72	11.33	10.52	11.11

Table 4.3. PCT Release Data for Spinel Matrix Glasses (continued).

	HLW06-08	HLW06-09	HLW06-10	HLW06-11	HLW06-12	HLW06-13	HLW06-14
	Leachate Concentration (ppm)						
B	14.120	30.860	13.680	15.350	59.490	6.553	48.440
Li	0.623	19.650	0.367	0.433	17.000	0.323	16.400
Na	93.660	184.500	46.410	54.600	150.400	55.270	115.200
Si	63.930	97.780	40.290	37.680	71.130	36.750	50.220
	Normalized Leachate Concentration (g/l)						
B	0.700	1.529	0.401	0.449	1.742	0.325	1.418
Li	0.536	1.410	0.316	0.373	1.220	0.278	1.177
Na	0.902	1.776	0.447	0.526	1.448	0.532	1.109
Si	0.342	0.598	0.216	0.230	0.435	0.225	0.307
	Normalized Mass Loss (g/m^2)						
B	0.350	0.765	0.200	0.225	0.871	0.162	0.709
Li	0.268	0.705	0.158	0.186	0.610	0.139	0.588
Na	0.451	0.888	0.223	0.263	0.724	0.266	0.555
Si	0.171	0.299	0.108	0.115	0.217	0.112	0.153
	Normalized Leach Rate (g/(m^2-day))						
B	0.050	0.109	0.029	0.032	0.124	0.023	0.101
Li	0.038	0.101	0.023	0.027	0.087	0.020	0.084
Na	0.064	0.127	0.032	0.038	0.103	0.038	0.079
Si	0.024	0.043	0.015	0.016	0.031	0.016	0.022
Leachate pH	10.71	11.32	9.95	10.12	10.94	10.51	11.02

Table 4.3. PCT Release Data for Spinel Matrix Glasses (continued).

	HLW06-15	HLW06-16	HLW06-17	HLW06-18	HLW06-19	HLW06-20	HLW06-21
	Leachate Concentration (ppm)						
B	111.800	24.230	9.383	11.140	14.400	13.470	17.830
Li	27.610	10.590	7.390	0.373	0.263	9.190	0.180
Na	342.200	244.200	72.960	37.130	152.400	88.710	227.400
Si	80.120	93.430	60.050	28.650	72.160	64.590	118.100
	Normalized Leachate Concentration (g/l)						
B	3.273	1.201	0.465	0.326	0.713	0.667	1.335
Li	1.981	0.760	0.530	0.321	0.226	0.659	—[1]
Na	2.306	1.646	0.702	0.357	1.027	0.854	1.533
Si	0.490	0.571	0.321	0.153	0.441	0.395	0.652
	Normalized Mass Loss (g/m^2)						
B	1.637	0.600	0.232	0.163	0.357	0.334	0.668
Li	0.991	0.380	0.265	0.161	0.113	0.330	—
Na	1.153	0.823	0.351	0.179	0.514	0.427	0.766
Si	0.245	0.286	0.161	0.077	0.221	0.197	0.326
	Normalized Leach Rate ($g/(m^2$-day))						
B	0.234	0.086	0.033	0.023	0.051	0.048	0.095
Li	0.142	0.054	0.038	0.023	0.016	0.047	—
Na	0.165	0.118	0.050	0.026	0.073	0.061	0.109
Si	0.035	0.041	0.023	0.011	0.032	0.028	0.047
Leachate pH	11.72	11.75	11.22	9.81	11.46	11.33	10.36

[1] — indicates empty data field. No normalization is performed because Li is not present in glass.

Table 4.3. PCT Release Data for Spinel Matrix Glasses (continued).

	HLW06-22	HLW06-23	HLW06-24	HLW06-25	HLW06-26	HLW06-27	HLW06-28
	Leachate Concentration (ppm)						
B	12.450	29.810	3.307	21.450	20.090	13.310	209.300
Li	9.780	0.147	Not Detected	13.130	0.067	15.270	101.300
Na	13.420	273.300	128.800	5.187	429.100	1.373	83.880
Si	13.400	112.700	43.320	47.260	134.100	76.950	159.000
	Normalized Leachate Concentration (g/l)						
B	0.267	2.233	0.248	0.461	1.505	0.437	4.494
Li	0.350	—[1]	—	0.470	—	0.547	3.629
Na	0.264	1.842	1.068	0.189	2.892	0.050	3.056
Si	0.083	0.695	0.281	0.239	0.869	0.310	0.796
	Normalized Mass Loss (g/m^2)						
B	0.134	1.116	0.124	0.230	0.752	0.218	2.247
Li	0.175	—	—	0.235	—	0.273	1.814
Na	0.132	0.921	0.534	0.094	1.446	0.025	1.528
Si	0.041	0.348	0.140	0.120	0.435	0.155	0.398
	Normalized Leach Rate (g/(m^2-day))						
B	0.019	0.159	0.018	0.033	0.107	0.031	0.321
Li	0.025	—	—	0.034	—	0.039	0.259
Na	0.019	0.132	0.076	0.013	0.207	0.004	0.218
Si	0.006	0.050	0.018	0.017	0.062	0.022	0.057
Leachate pH	10.22	11.91	11.43	9.81	11.79	9.95	9.83

[1] — indicates empty data field. No normalization is performed because Li is not present in glass.

Table 4.3. PCT Release Data for Spinel Matrix Glasses (continued).

	HLW06-29	HLW06-30	HLW06-31	HLW06-32	HLW06-33	HLW06-34	HLW06-35
	Leachate Concentration (ppm)						
B	3.590	14.350	2.493	551.200	1.687	578.800	15.440
Li	17.850	0.037	8.503	0.203	7.107	0.917	8.747
Na	12.700	177.200	5.447	1073.000	5.743	977.300	38.850
Si	60.060	85.980	21.53	146.200	11.41	45.050	45.900
	Normalized Leachate Concentration (g/l)						
B	0.269	1.075	0.187	11.835	0.126	12.427	0.488
Li	0.639	—[1]	0.333	—	0.323	—	0.574
Na	0.463	1.194	0.198	7.231	0.209	6.586	0.440
Si	0.295	0.524	0.128	0.836	0.074	0.292	0.249
	Normalized Mass Loss (g/m^2)						
B	0.134	0.537	0.093	5.917	0.063	6.214	0.244
Li	0.320	—	0.167	—	0.162	—	0.287
Na	0.231	0.597	0.099	3.616	0.105	3.293	0.220
Si	0.147	0.262	0.064	0.418	0.037	0.146	0.125
	Normalized Leach Rate ($g/(m^2$-day))						
B	0.019	0.077	0.013	0.845	0.009	0.888	0.035
Li	0.046	—	0.024	—	0.023	—	0.041
Na	0.033	0.085	0.014	0.517	0.015	0.470	0.031
Si	0.021	0.037	0.009	0.060	0.005	0.021	0.018
Leachate pH	10.81	11.38	10.67	10.45	10.68	10.18	10.54

[1] — indicates empty data field. No normalization is performed because Li is not present in glass.

Table 4.4. Normalized PCT Release Data and Standard Deviations for Replicates Among the Spinel Matrix Glasses.

Glass IDs of Replicate Pairs	Normalized PCT Releases (g/l)		
	Boron	Lithium	Sodium
HLW06-01	0.630	0.507	0.660
HLW06-17	0.465	0.530	0.702
% Relative Standard Deviation	**21.35**	**3.13**	**4.46**
HLW06-06	0.324	0.407	0.469
HLW06-13	0.325	0.278	0.532
% Relative Standard Deviation	**0.25**	**26.65**	**8.85**
Pooled % Relative Standard Deviation	**15.10**	**18.97**	**7.01**

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

Test Name	HLW06-Glasses Tested	PCT Results (Normalized Releases in g/l and Leachate pH)				
		Boron	Lithium	Sodium	Silicon	pH
HR7C	-01, -16, -24,-25, -35	18.233	9.391	12.139	3.580	11.79
HR7D	-17, -19, -20, -23, -31	16.508	9.047	11.089	3.567	11.78
HR7E	-03, -07, -11, -15, -34	16.641	8.806	10.932	3.412	11.73
HR7F	-06, -18, -22, -26, -33	17.436	8.991	11.527	3.477	11.76
HR7G	-02, -05, -14, -27, -28	18.236	9.672	12.735	3.829	11.82
HR7H	-04, -08, -09, -12, -21	14.859	8.919	11.048	3.360	11.76
HR7I	-10, -13, -29, -30, -32	17.093	9.493	12.338	3.549	11.75
Mean and Standard Deviation		17.001 ± 1.169	9.188 ± 0.328	11.687 ± 0.717	3.539 ± 0.152	11.77 ± 0.03
% Relative Standard Deviation		6.88	3.57	6.14	4.30	0.25
Reference Glass DWPF-EA [14]		16.695 ± 1.222	9.565 ± 0.735	13.346 ± 0.902	3.922 ± 0.376	11.85 ± 0.10

Table 4.6. Temperature and Volume %-Crystallinity Data for Non-Spinel Matrix Glasses.

Glass ID	Temperature (°C)										
	700	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**	**1150**	**1200**
HLW05-01	—[1]	***0.7***	1.0	0.9	—	0.8	—	0.4	—	—	—
HLW05-02	***0.9***[2]	1.1	0.7	0.6	—	0.3	—	—	—	—	—
HLW05-03	***0.1***	0.8	0.2	0.1	—	***0.1***	—	—	—	—	—
HLW05-04	***0.4***	***0.3***	0.7	0.4	—	0.2	—	—	—	—	—
HLW05-05	0.1	0.2	—	0.1	—	0.1	—	—	—	—	—
HLW05-06	—	—	—	3.0	—	2.1	—	0.9	1.0	0.1	—
HLW05-07	***0.6***	1.0	0.6	0.5	—	0.2	—	—	—	—	—
HLW05-08	—	***0.7***	***0.9***	1.7	—	1.6	—	1.0	0.7	0.9	—
HLW05-09	0.9	0.9	—	0.2	—	0.1	—	***0.1***	—	—	—
HLW05-10		***0.4***	***0.9***	1.1	—	1.0	—	0.4	0.3	0.1	—
HLW05-11	1.0	***0.3***	0.4	0.4	—	0.2	—	—	—	—	—
HLW05-12	—	***0.7***	—	2.7	—	1.6	—	0.9	1.1	0.5	—
HLW05-13	—	***7.7***	0.8	0.7	—	0.7	—	0.2	—	—	—
HLW05-14	1.0	0.7	—	0.3	—	0.1	—	—	—	—	—
HLW05-15	0.1	0.1	0.1	0.3	—	0.1	—	—	—	—	—
HLW05-16	—	—	—	3.2	—	2.9	—	2.1	1.7	1.9	1.9
HLW05-17	—	***2.5***	—	2.7	—	1.6	—	1.2	0.9	0.7	—
HLW05-18	—	—	—	***3.5***	—	***4.8***	—	8.9	2.3	2.2	2.6
HLW05-19	—	—	—	***29.9***	—	***17.1***	—	2.1	—	0.9	—
HLW05-20	3.1	0.2	0.2	***0.1***	—	***0.1***	—	***0.1***	—	—	***0.1***

[1] — indicates empty data field. No data were collected for those specific temperatures.
[2] Data in bolded italics were not used in estimating $T_{1\%}$.

Table 4.6. Temperature and Volume %-Crystallinity Data for Non-Spinel Matrix Glasses (continued).

Glass ID	Temperature (°C)										
	700	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**	**1150**	**1200**
HLW05-21	0.1	0.1	—	0.1	—	0.1	—	—	—	—	—
HLW05-22	1.0	—	0.5	0.5	—	0.1	—	—	—	—	—
HLW05-23	—[1]	—	—	1.5	—	1.1	—	0.8	0.9	0.8	0.7
HLW05-24	—	—	—	17.5	—	10.8	—	8.9	—	5.9	2.4
HLW05-25	—	—	—	8.4	—	6.0	—	4.2	3.9	2.6	2.0
HLW05-26	—	—	—	18.9	—	16.3	—	10.5	—	3.7	0.1
HLW05-27	***9.7***[2]	—	1.4	0.7	—	0.6	—	—	—	—	—
HLW05-28	—	—	—	***3.4***	—	6.3	—	3.5	2.3	2.3	2.2
HLW05-29	—	—	—	19.8	—	15.9	—	10.9		4.6	0.1
HLW05-30	0.4	—	0.3	0.2	—	0.1	—	—	—	—	—

[1] — indicates empty data field. No data were collected for those specific temperatures.
[2] Data in bolded italics were not used in estimating $T_{1\%}$.

Table 4.7. Temperature and Volume %-Crystallinity Data for Spinel Matrix Glasses.

Glass ID	Temperature (°C)										
	700	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**	**1150**	**1200**
HLW06-01	4.4	—	2.7	—	—	2.0	1.0	1.0	—	—	—
HLW06-02	—[1]	2.4	1.9	1.5	—	1.1	0.3	0.3	—	—	—
HLW06-03	—	—	—	5.6	—	4.7	—	2.7	2.0	2.9	1.2
HLW06-04	—	***10.3***[2]	—	1.0	0.6	0.6	0.2	0.1	—	—	—
HLW06-05	—	1.7	1.3	1.8	0.9	0.9	0.3	—	—	—	—
HLW06-06	—	—	—	***3.7***	—	4.1	3.9	3.1	2.2	2.5	1.3
HLW06-07	—	—	—	8.5	—	5.5	—	2.5	3.1	2.6	1.5
HLW06-08	—	—	—	2.2	1.7	1.6	—	0.9	0.9	0.3	—
HLW06-09	—	—	—	***3.7***	—	4.6	3.3	2.3	3.0	1.8	1.1
HLW06-10	—	—	—	1.4	1.5	1.0	1.3	1.0	0.6	0.5	0.3
HLW06-11	—	—	—	4.0	—	2.9	—	1.3	1.0	1.3	0.4
HLW06-12	—	—	2.8	2.7	2.3	1.0	1.4	1.1	0.1	—	—
HLW06-13	—	—	—	***3.6***	—	***2.4***	3.7	3.2	2.2	1.6	0.5
HLW06-14	—	2.8	—	2.1	1.4	1.3	0.7	0.4	—	—	—
HLW06-15	—	***2.4***	—	2.4	1.5	0.6	0.1	—	—	—	—
HLW06-16	***13.1***	***11.5***	3.2	—	2.1	1.0	0.5	—	—	—	—
HLW06-17	***6.0***	—	—	—	2.2	1.8	1.1	1.0	0.4	—	—
HLW06-18	—	—	—	2.9	—	2.0	1.2	1.1	0.6	0.9	—
HLW06-19	—	—	—	—	—	5.2	—	2.7	1.5	2.1	1.1
HLW06-20	—	***19.6***	—	—	—	2.2	2.1	1.9	1.2	0.9	—

[1] — indicates empty data field. No data were collected for those specific temperatures.
[2] Data in bolded italics were not used in estimating $T_{1\%}$.

Table 4.7. Temperature and Volume %-Crystallinity Data for Spinel Matrix Glasses (continued).

Glass ID	**Temperature (°C)**										
	700	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**	**1150**	**1200**
HLW06-21	—[1]	***21.9***[2]	—	2.0	1.6	***4.7***	1.2	1.4	—	1.1	—
HLW06-22	—	***0.3***	***0.2***	0.4	0.4	0.2	—	—	—	—	—
HLW06-23	—	—	—	—	—	***23.2***	—	13.4	8.5	6.0	3.3
HLW06-24	—	***49.9***	***41.5***	—	—	***28.6***	1.9	2.3	—	1.5	1.3
HLW06-25	—	—	3.0	—	—	1.6	1.5	0.8	0.8	—	—
HLW06-26	—	***22.8***	—	***12.3***	—	***3.3***	5.6	5.5	4.5	4.7	—
HLW06-27	—	12.2	—	11.0	—	7.5	—	7.0	—	5.6	4.6
HLW06-28	—	—	***5.8***	***0.8***	1.3	1.3	0.5	0.6	—	—	—
HLW06-29	—	—	—	***17.7***	—	10.9	—	5.4	7.5	5.8	3.2
HLW06-30	—	—	—	***23.3***	—	***14.3***	—	1.7	0.8	0.7	0.1
HLW06-31	—	—	—	***7.4***	—	7.6	—	6.6	—	3.4	2.9
HLW06-32	—	2.5	2.3	0.9	1.1	0.5	0.4	—	—	—	—
HLW06-33	—	***19.1***	—	3.7	—	3.4	3.0	3.3	2.1	2.0	—
HLW06-34	—	***2.8***	—	13.7	5.6	0.2	***0.1***	—	—	—	—
HLW06-35	—	2.7	2.1	—	0.6	0.5	0.5	—	—	—	—

[1] — indicates empty data field. No data were collected for those specific temperatures.
[2] Data in bolded italics were not used in estimating $T_{1\%}$.

Table 4.8. Regression Results, Estimated $T_{1\%}$, and the Major Crystalline Phase Near $T_{1\%}$ for Non-Spinel Matrix Glasses.

Glass ID	Intercept	Slope	$T_{1\%}$ (°C)	Crystalline Phase
HLW05-01	1225.3012	-403.6145	821.69	ThO_2 (60%) + Spinel (40%)
HLW05-02	1004.9618	-248.0916	756.87	Spinel (100%)
HLW05-03	844.7674	-122.0930	722.67	Spinel (100%)
HLW05-04	992.1053	-289.4737	702.63	Spinel (100%)
HLW05-05	ND[1]	ND	ND	(Trace amount of Spinel)
HLW05-06	1168.1235	-104.3124	1063.81	ZrO_2 (65%) + ThO_2 (35%)
HLW05-07	980.1527	-248.0916	732.06	Spinel (100%)
HLW05-08	1316.4975	-251.2690	1065.23	ZrO_2 (100%)
HLW05-09	938.5463	-240.0881	698.46	Spinel (100%)
HLW05-10	1173.0964	-263.9594	909.14	ThO_2 (75%) [+ Spinel 25%]
HLW05-11	963.8889	-277.7778	686.11	Spinel (100%)
HLW05-12	1205.1532	-136.1421	1069.01	ZrO_2 (70%) [+ThO_2 30%]
HLW05-13	1130.6818	-363.6364	767.05	Spinel (75%) [+ ThO_2 25%]
HLW05-14	953.8462	-269.2308	684.62	Spinel (80%) [+ Sodium/Uranium/Strontium Oxide 20%]
HLW05-15	ND	ND	ND	(Trace Amount of Spinel and Noble Metal)
HLW05-16	1497.3963	-195.9400	1301.46	ZrO_2 (100%)
HLW05-17	1257.7586	-176.7241	1081.03	ZrO_2 (100%)
HLW05-18	1184.1900	-14.7975	1169.39	$ZrSiO_4$ (100%)
HLW05-19	1225.0000	-83.3333	1141.67	ThO_2 (100%)
HLW05-20	780.1724	-25.8621	754.31	Sodium/Aluminum Silicate (100%)
HLW05-21	ND	ND	ND	(Trace Amount of Spinel and Noble Metal)
HLW05-22	969.9387	-276.0736	693.87	Uranium Oxide (100%)
HLW05-23	1451.5385	-415.3846	1036.15	ThO_2 (100%)
HLW05-24	1264.6346	-24.6851	1239.95	ZrO_2 (75%) [+$Na_2ZrSi_2O_7$ 25%]
HLW05-25	1298.0493	-54.9187	1243.13	$ZrSiO_4$ (100%)
HLW05-26	1214.6379	-17.6402	1197.00	$Na_2ZrSi_2O_7$ (100%)
HLW05-27	996.9298	-144.7368	852.19	Spinel (100%)
HLW05-28	1257.7890	-50.5389	1207.25	$ZrSiO_4$ (100%)
HLW05-29	1221.0738	-17.6485	1203.43	$Na_2ZrSi_2O_7$ (99%) [+ Zirconia 1%]
HLW05-30	ND	ND	ND	(Trace amount of Spinel)

[1]ND = Not determined (Regression was not performed).

Table 4.9. Regression Results, Estimated $T_{1\%}$, and the Major Crystalline Phase Near $T_{1\%}$ for Spinel Matrix Glasses.

Glass ID	Intercept	Slope	$T_{1\%}$ (°C)	Crystalline Phase
HLW06-01	1121.7782	-99.9001	1021.88	Spinel (100%)
HLW06-02	1070.2201	-136.1761	934.04	Spinel (100%)
HLW06-03	1285.4889	-73.9756	1211.51	Spinel (85%) [+ ZrO_2 15%]
HLW06-04	1055.7692	-211.5385	844.23	Spinel (99%) [+ $Na_2ZrSi_2O_7$ 1%]
HLW06-05	1039.0282	-142.6332	896.40	Spinel (100%)
HLW06-06	1314.8018	-84.1410	1230.66	Spinel (75%) [+ ZrO_2 25%]
HLW06-07	1238.4017	-47.6966	1190.71	Spinel (100%)
HLW06-08	1213.4831	-168.5393	1044.94	Spinel (100%)
HLW06-09	1263.2989	-70.1735	1193.13	Spinel (100%)
HLW06-10	1269.3841	-257.2464	1012.14	Spinel (100%)
HLW06-11	1218.7921	-92.9131	1125.88	Spinel (100%)
HLW06-12	1114.6307	-101.0890	1013.54	Spinel (100%)
HLW06-13	1238.0160	-61.6143	1176.40	Spinel (95%) [+ ZrO_2 5%]
HLW06-14	1091.6984	-120.7116	970.99	Spinel (100%)
HLW06-15	997.5728	-63.1068	934.47	Spinel (100%)
HLW06-16	1031.9700	-70.2765	961.69	Spinel (100%)
HLW06-17	1143.0000	-110.0000	1033.00	Spinel (100%)
HLW06-18	1189.1425	-118.9488	1070.19	Spinel (100%)
HLW06-19	1228.4456	-54.9387	1173.51	Spinel (100%)
HLW06-20	1268.0931	-131.3814	1136.71	Spinel (100%)
HLW06-21	1423.4375	-296.8750	1126.56	ThO_2 (100%)
HLW06-22	1025.0000	-375.0000	650.00	Unidentified Cr-Fe Oxide (100%)
HLW06-23	1240.5764	-14.8175	1225.76	ZrO_2 (95%) [+ ThO_2 5%]
HLW06-24	1396.6102	-169.4915	1227.12	ThO_2 (100%)
HLW06-25	1173.4530	-125.6188	1047.83	Spinel (55%) [+ ThO_2 45%]
HLW06-26	1581.1321	-99.7305	1481.40	$Na_2ZrSi_2O_7$ (85%) [+ ZrO_2 15%]
HLW06-27	1444.7668	-56.7558	1388.01	Zircon (95%) [+ ZrO_2 5%]
HLW06-28	1093.1718	-127.7533	965.42	Spinel (65%) [Unidentified Na-Ca-U oxide 25% + Unidentified Cr-Fe oxide 10%]
HLW06-29	1282.6248	-29.3635	1253.26	$ZrSiO_4$ (65%) [+ ZrO_2 35%]
HLW06-30	1202.2945	-93.6902	1108.60	Spinel (100%)
HLW06-31	1325.5508	-46.4489	1279.10	Spinel (75%) [+ ThO_2 25%]
HLW06-32	998.2063	-96.0049	902.20	Spinel (100%)
HLW06-33	1413.9535	-136.2126	1277.74	ZrO_2 (100%)
HLW06-34	947.5146	-7.3099	940.20	$Na_2ZrSi_2O_7$ (90%) [+Spinel 10%]
HLW06-35	1000.7326	-94.3223	906.41	Unidentified Cr-Fe Oxide (70%) [+ ThO_2 30%]

Table 4.10. $T_{1\%}$ Data and Standard Deviations for Replicates Among Non-Spinel Matrix and Spinel Matrix Glasses.

Glass IDs of Replicate Pairs	Estimated T1% (°C)	Standard Deviations (°C)
HLW05-02 HLW05-07	756.87 732.06	**17.54**
HLW05-06 HLW05-12	1063.81 1069.01	**3.68**
HLW05-18 HLW05-28	1169.39 1207.25	**26.77**
HLW05-26 HLW05-29	1197.00 1203.43	**4.54**
HLW06-01 HLW06-17	1021.88 1033.00	**7.86**
HLW06-06 HLW06-13	1230.66 1176.40	**38.37**
Standard Deviations Pooled Over 6 Replicate Pairs = **20.79**		

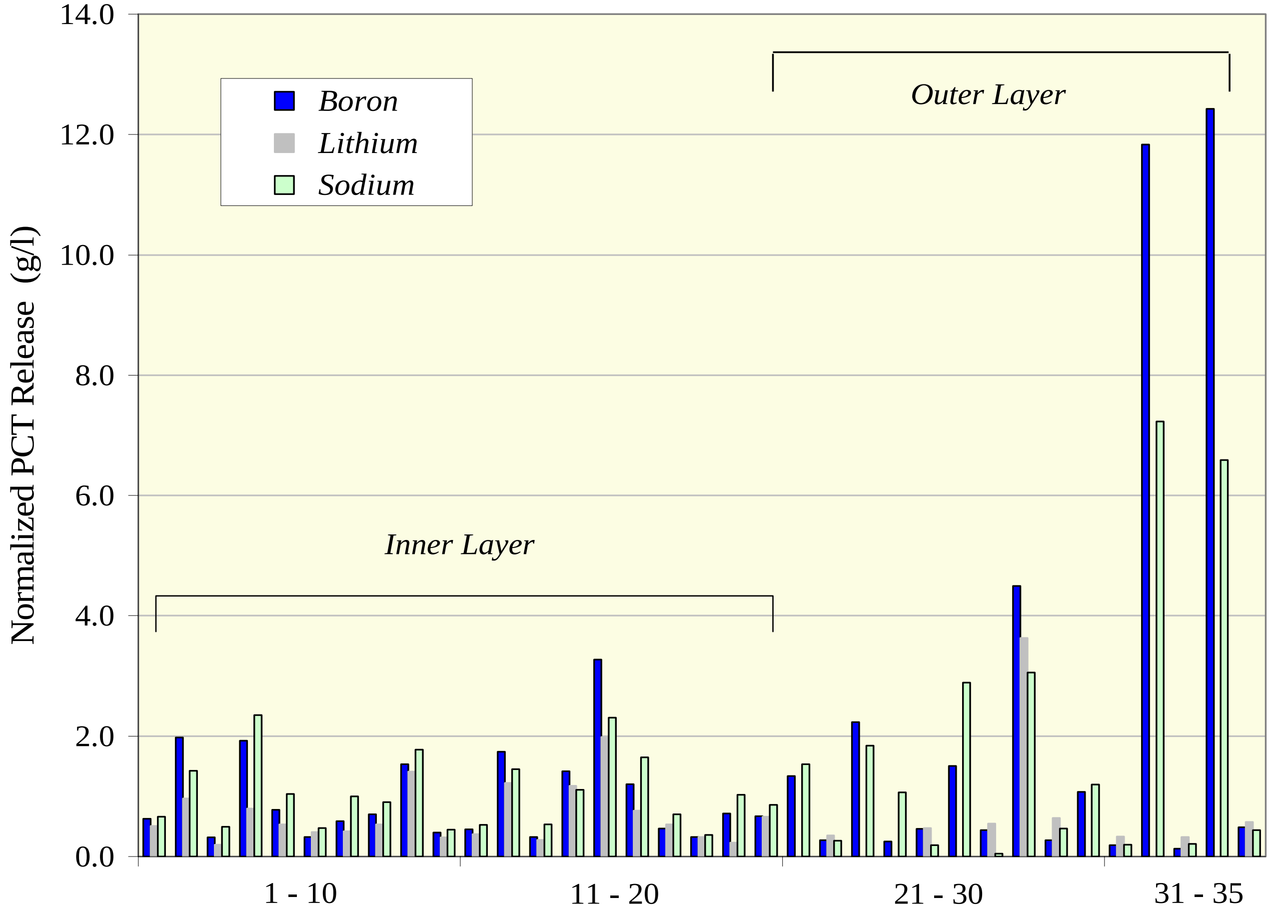


Figure 4.1. Normalized PCT Releases (Boron, Lithium, and Sodium) for the Spinel Matrix Glasses. (The index along the horizontal axis identifies the sample grouping (i.e., "01-10" identifies the samples HLW06-01 through -10, etc.).)

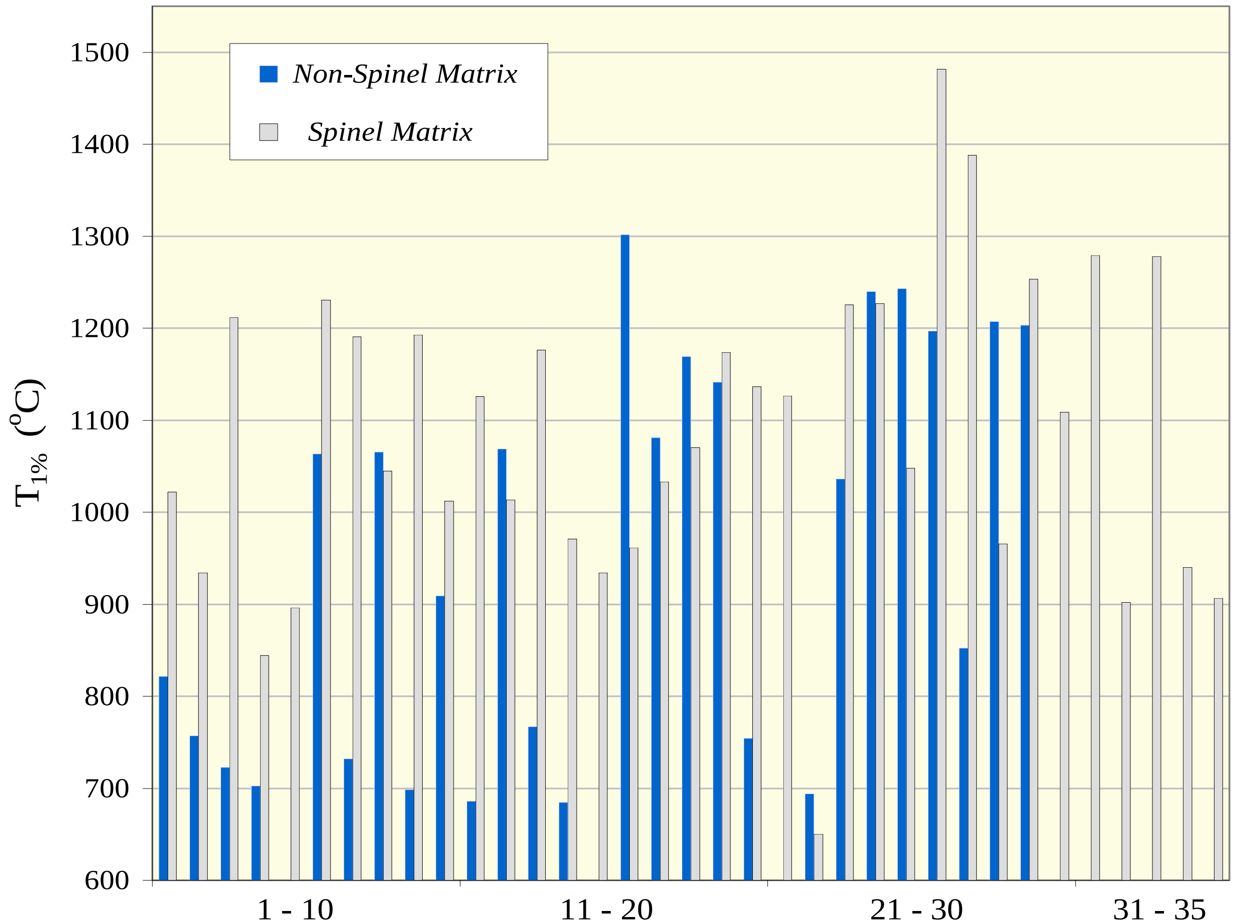


Figure 4.2. Estimated $T_{1\%}$ Values for the Non-Spinel Matrix and Spinel Matrix Glasses. (The index along the horizontal axis identifies the sample grouping (i.e., "01-10" identifies the samples HLW05-01 through -10 and HLW06-01 through -10, etc.).)

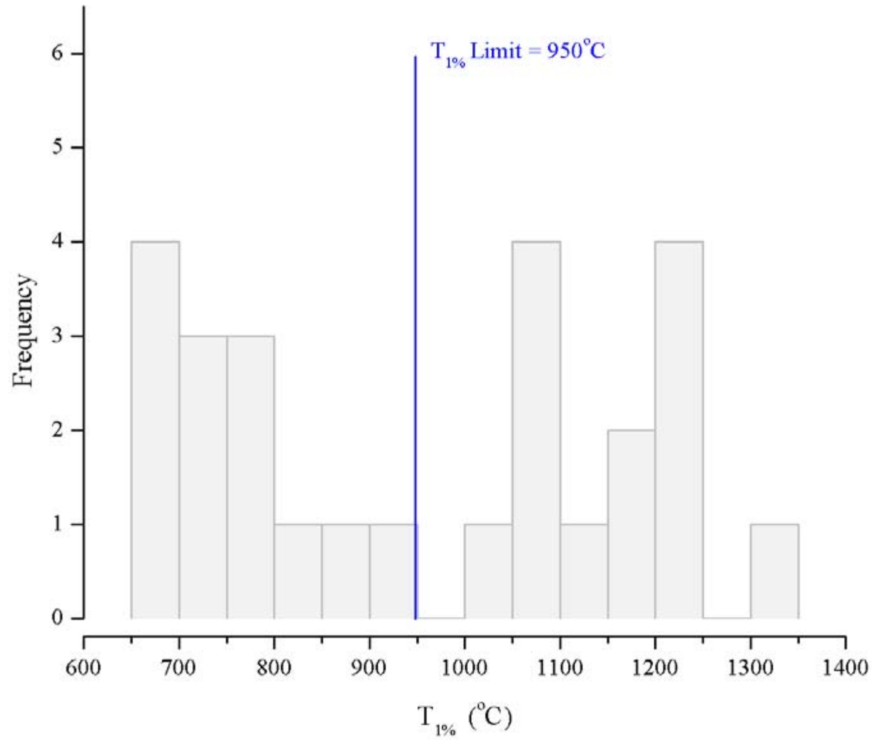


Figure 4.3. Histogram of Estimated $T_{1\%}$ Values for the Non-Spinel Matrix (26 Estimates).

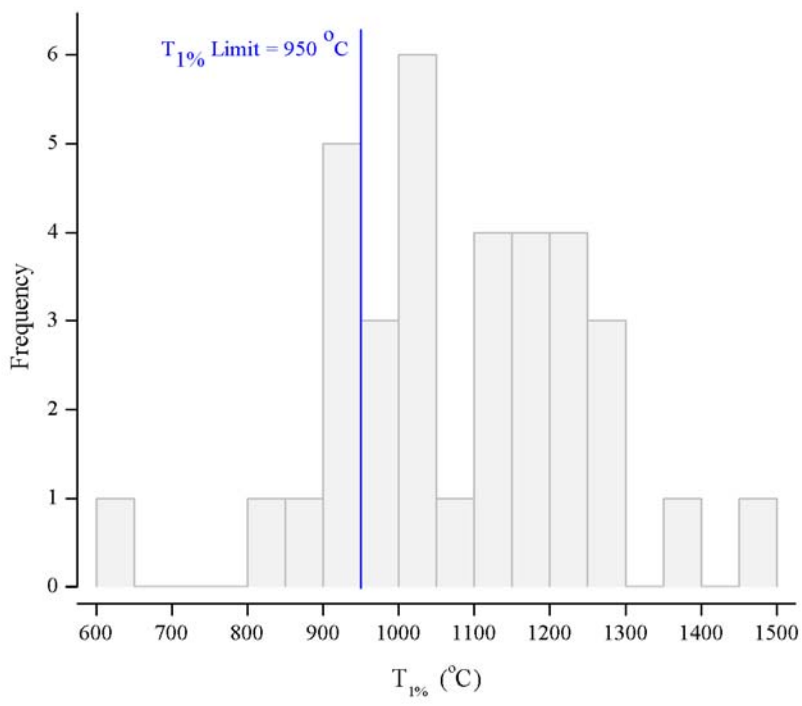
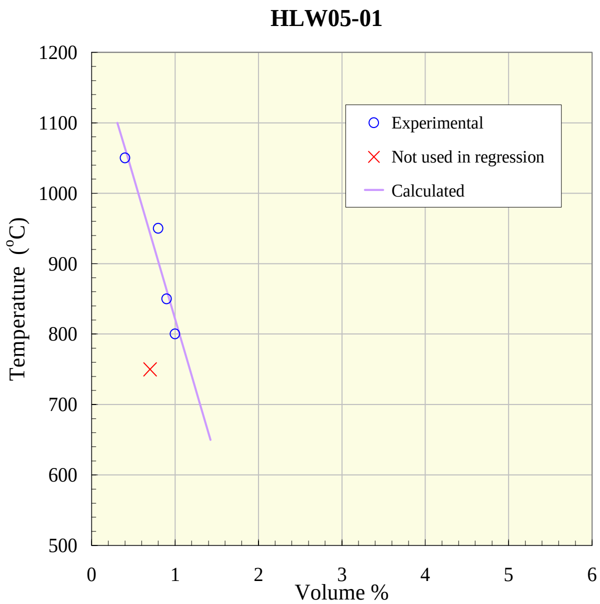
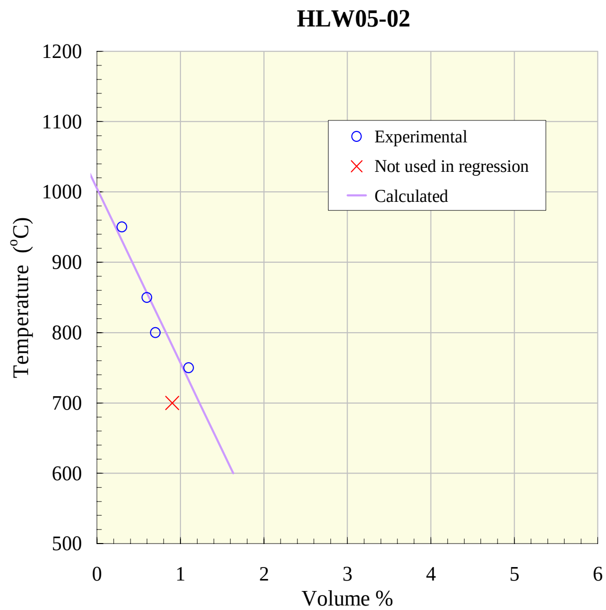


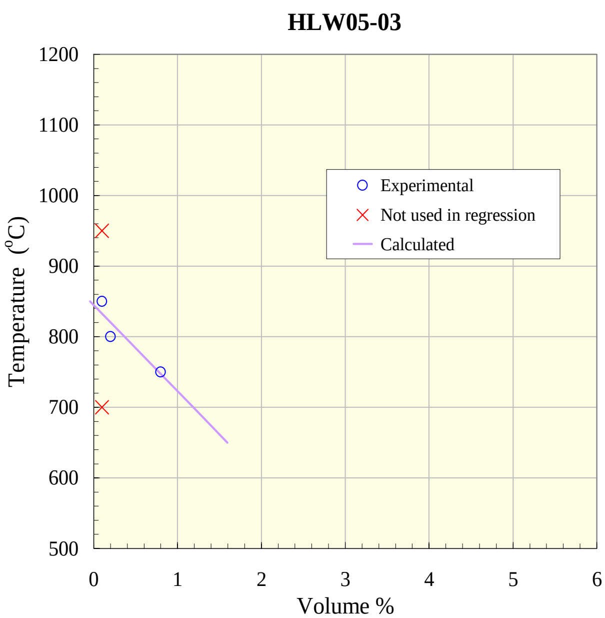
Figure 4.4. Histogram of Estimated $T_{1\%}$ Values for the Spinel Matrix (35 Estimates).

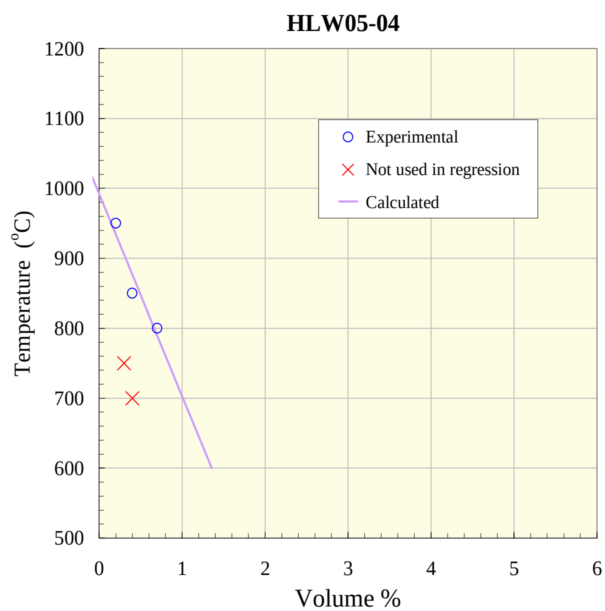
Appendix A
Plots of Heat Treatment and Regression Data

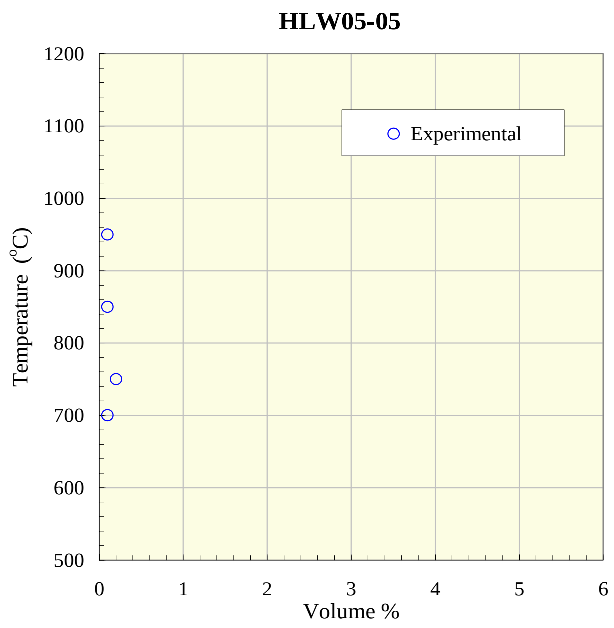
This appendix presents graphically heat treatment data collected for the Non-Spinel Matrix (HLW05- series) and Spinel Matrix (HLW06- series) glasses. For each of the 65 matrix glasses (30 HLW05- glasses and 35 HLW06- glasses), the volume % crystallinity data measured after heat treatment are plotted 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 4 HLW05- glasses, for which no regression was performed). To the extent possible, similar scales are used in the plots to facilitate comparison.

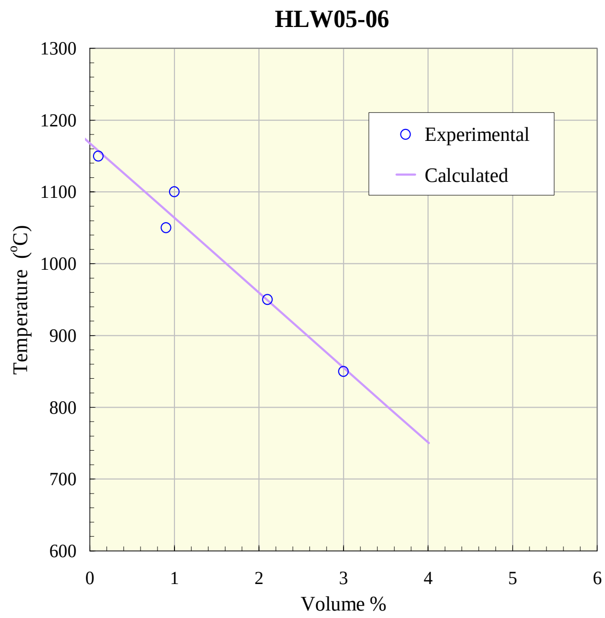

HLW05-01
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
1200
1100
1000
900
800
700
600
500
0
1
2
3
4
5
6


HLW05-02
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
1200
1100
1000
900
800
700
600
500
0
1
2
3
4
5
6

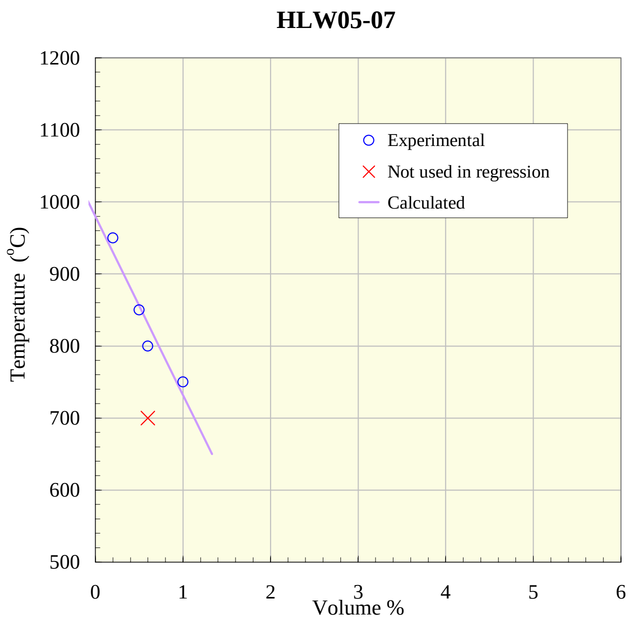

HLW05-03
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
1200
1100
1000
900
800
700
600
500
0
1
2
3
4
5
6

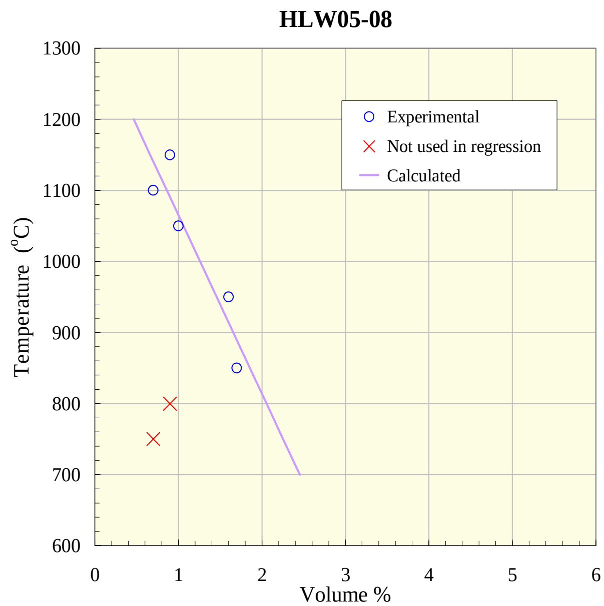

HLW05-04
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
1200
1100
1000
900
800
700
600
500
0
1
2
3
4
5
6

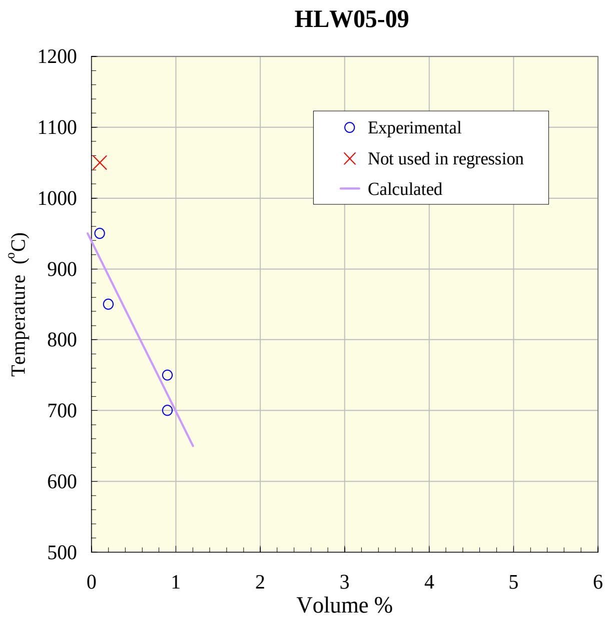


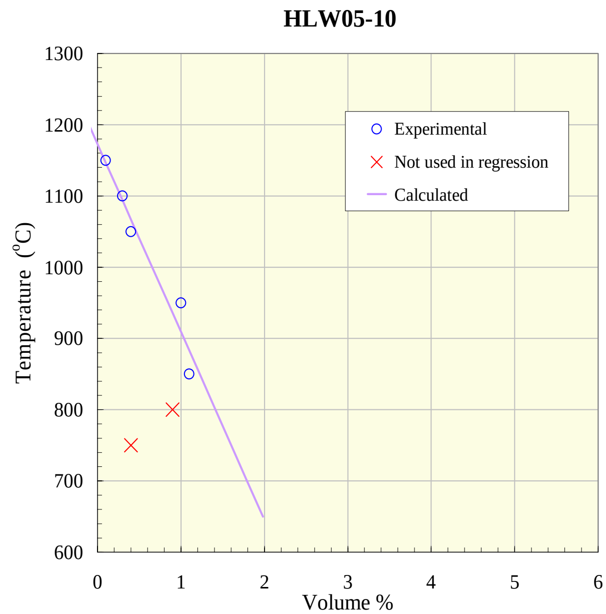


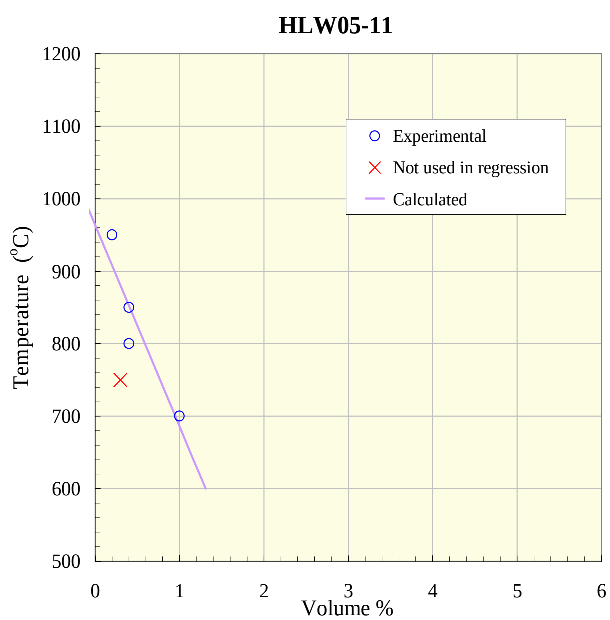
Note: Regression was not performed on the collected data

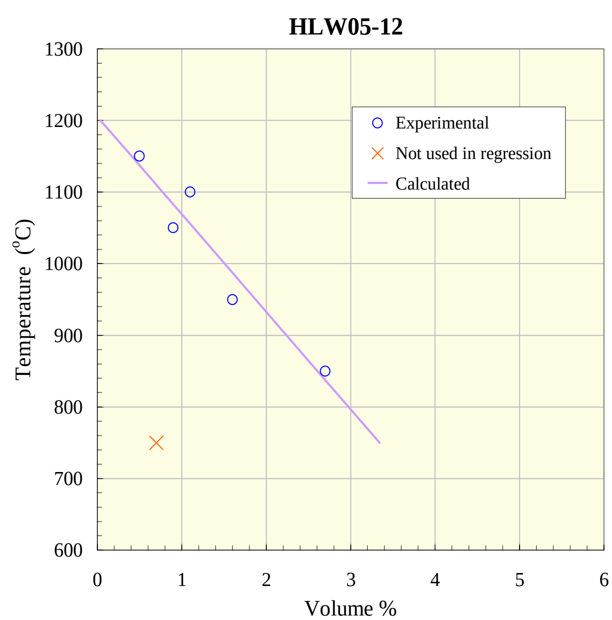


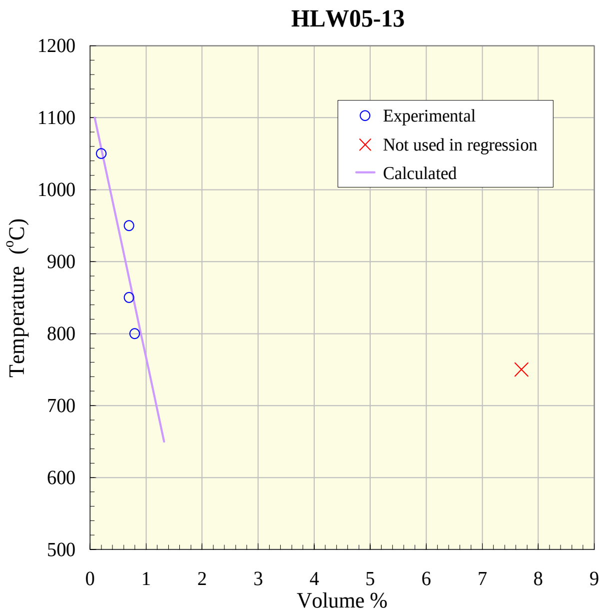


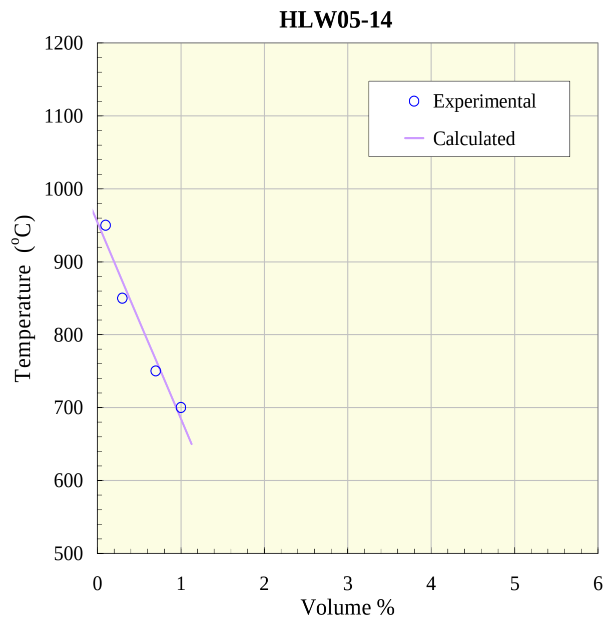

HLW05-09
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %

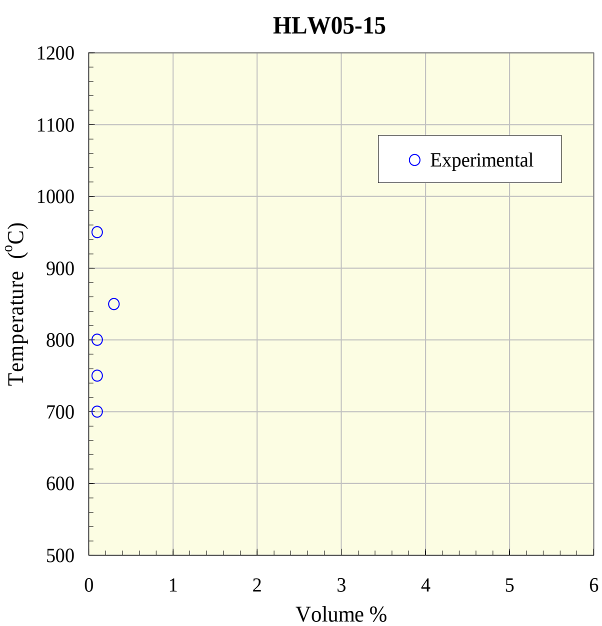

HLW05-10
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %

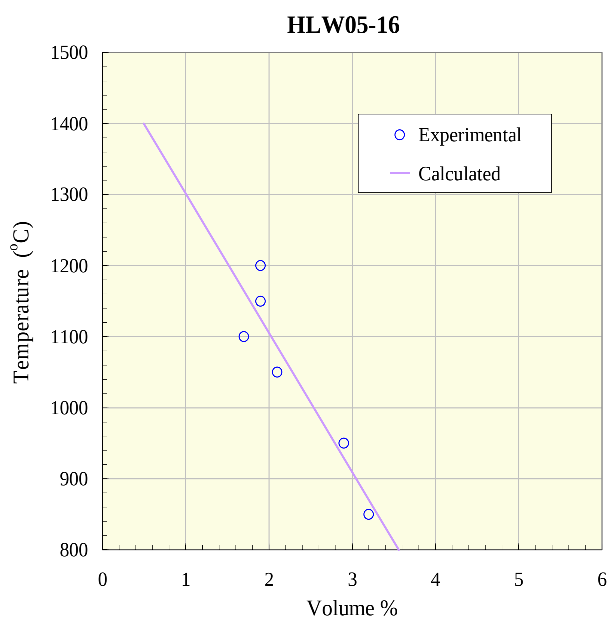

HLW05-11
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %


HLW05-12
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %

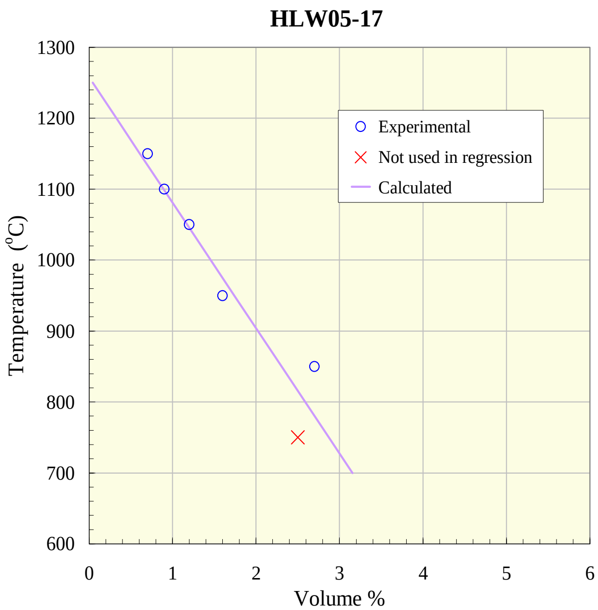


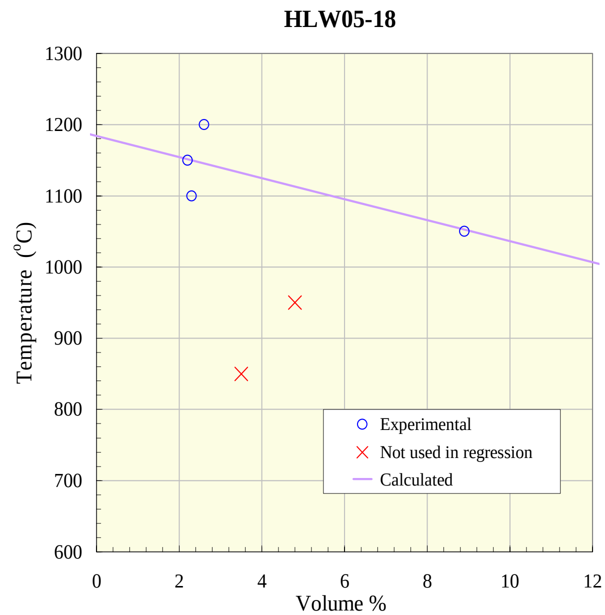


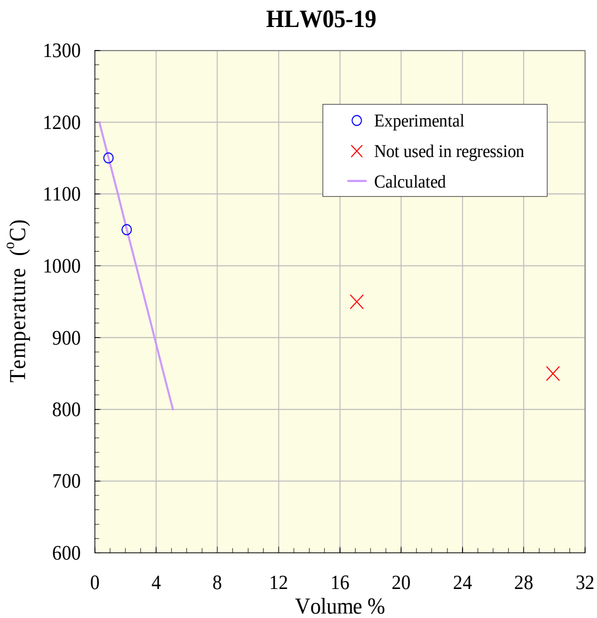


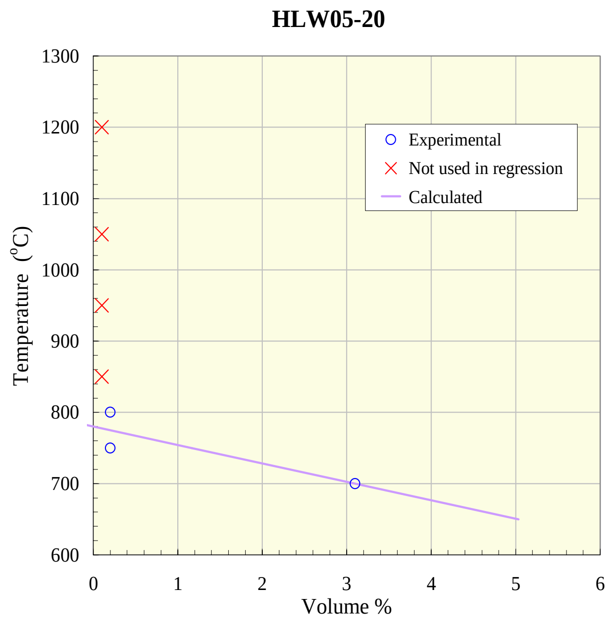


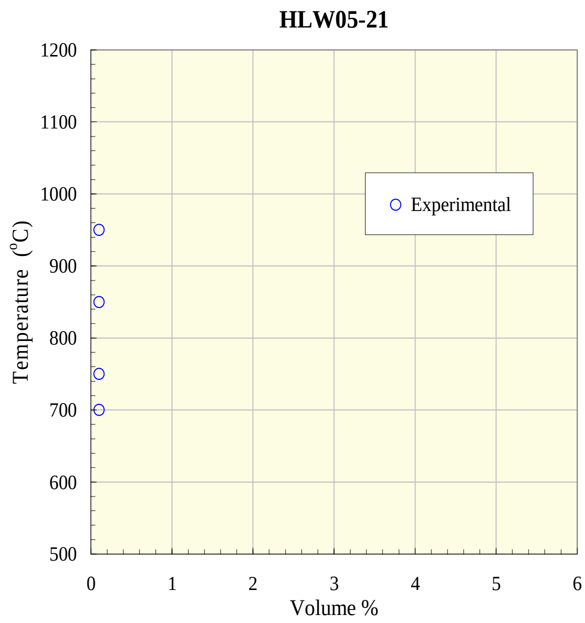
Note: Regression was not performed on the collected data


HLW05-17
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
1300
1200
1100
1000
900
800
700
600
0
1
2
3
4
5
6

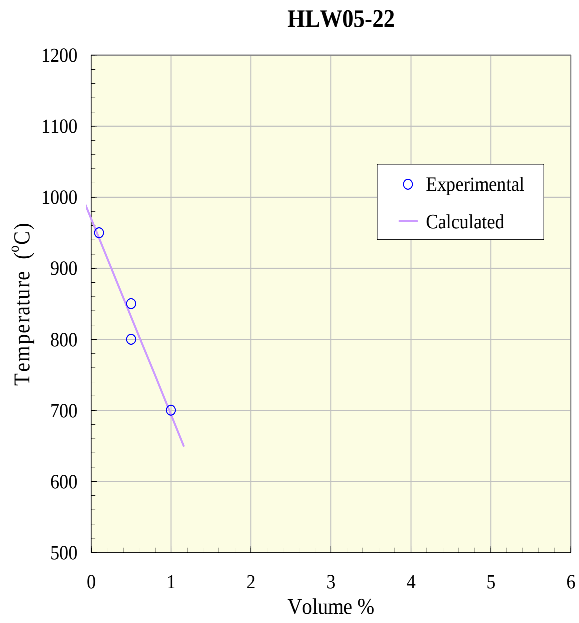

HLW05-18
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
1300
1200
1100
1000
900
800
700
600
0
2
4
6
8
10
12

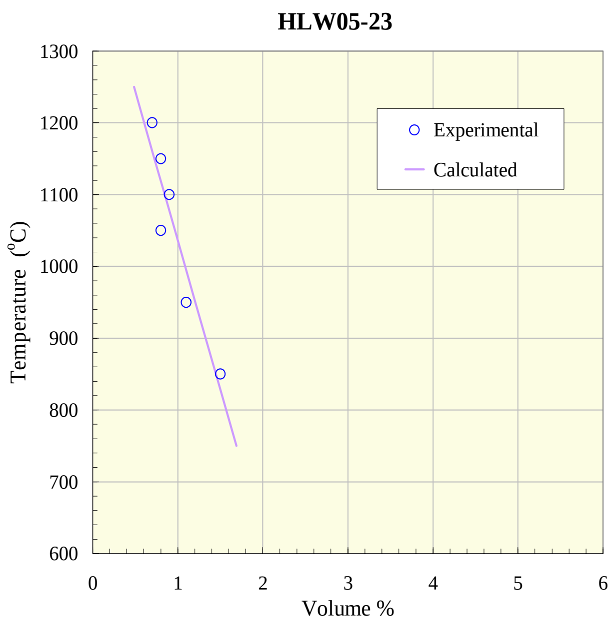

HLW05-19
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
1300
1200
1100
1000
900
800
700
600
0
4
8
12
16
20
24
28
32

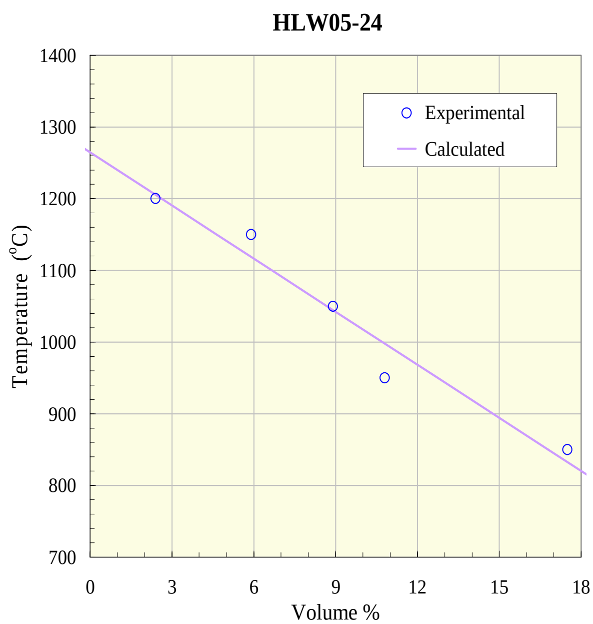

HLW05-20
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated
1300
1200
1100
1000
900
800
700
600
0
1
2
3
4
5
6



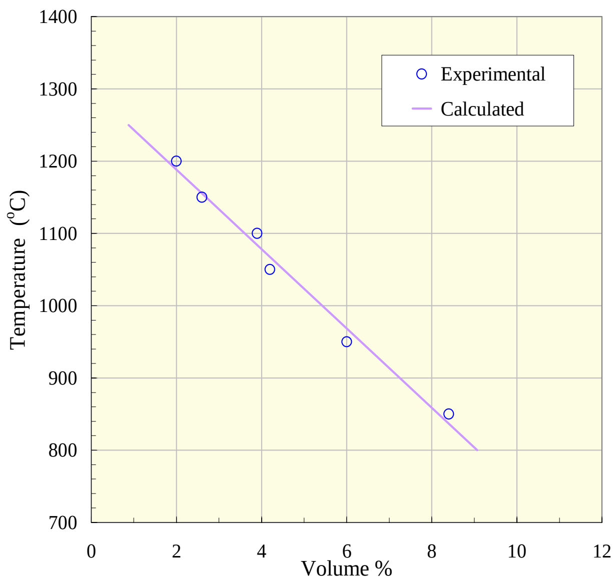
Note: Regression was not performed on the collected data



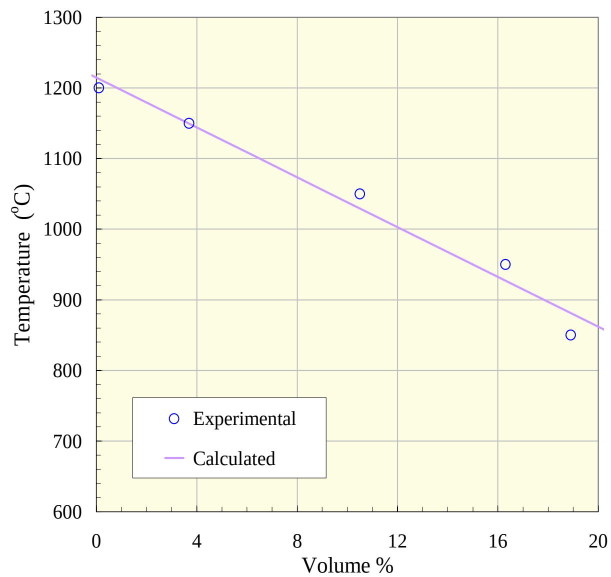




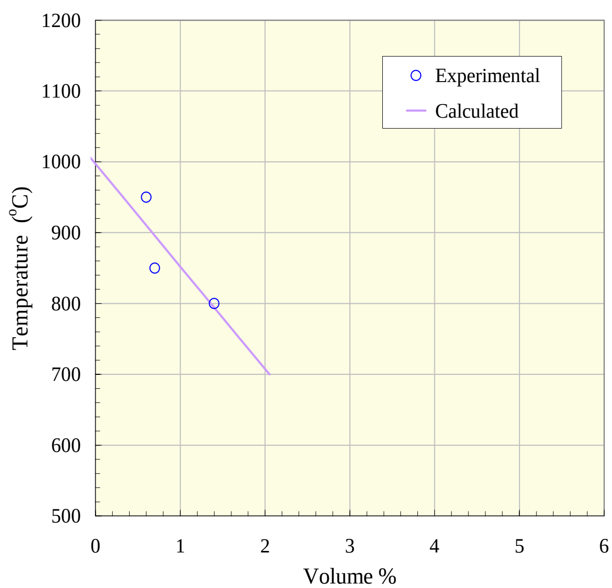
HLW05-25



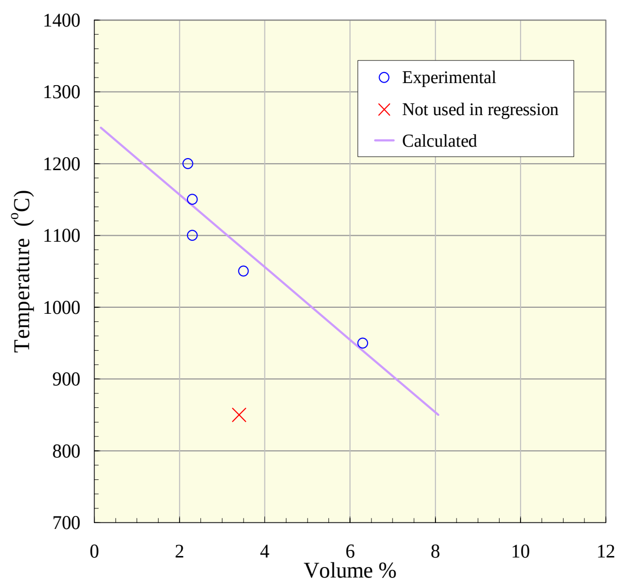
HLW05-26

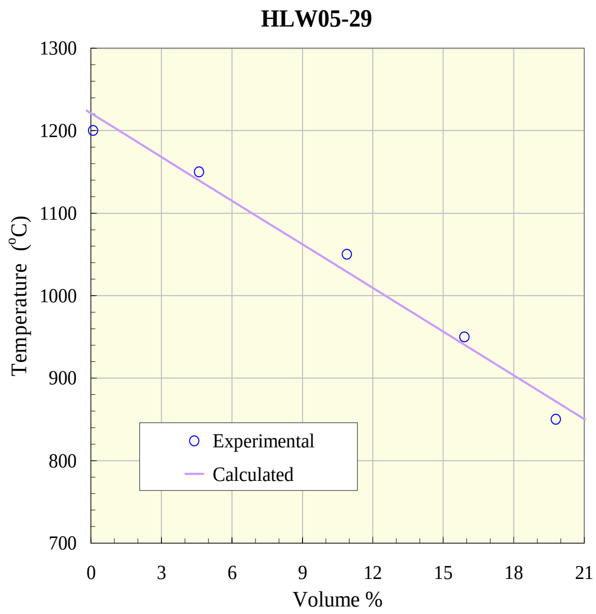


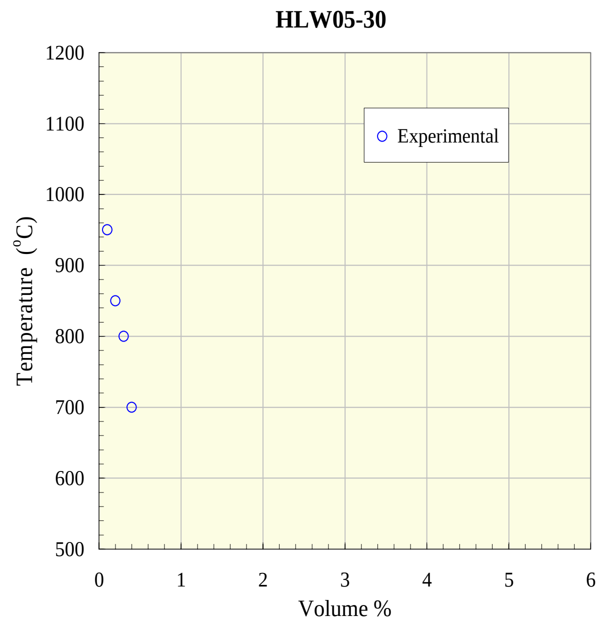
HLW05-27



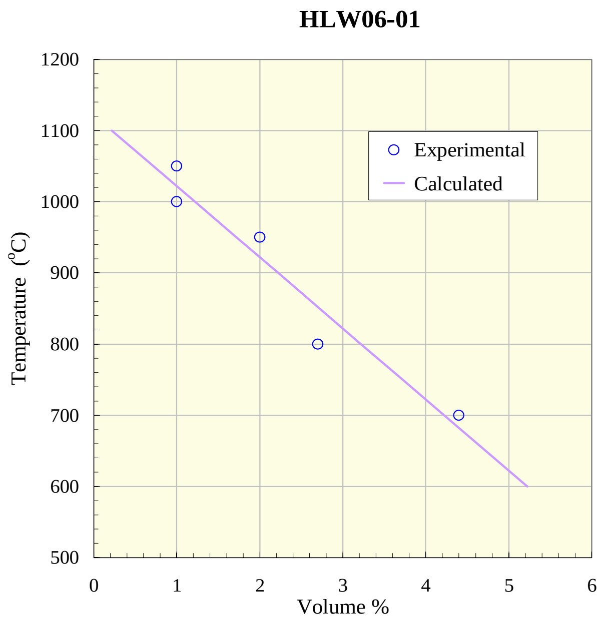
HLW05-28

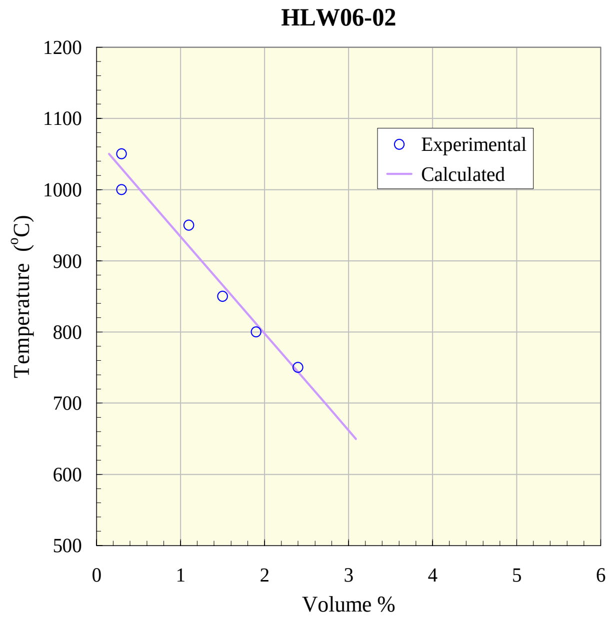


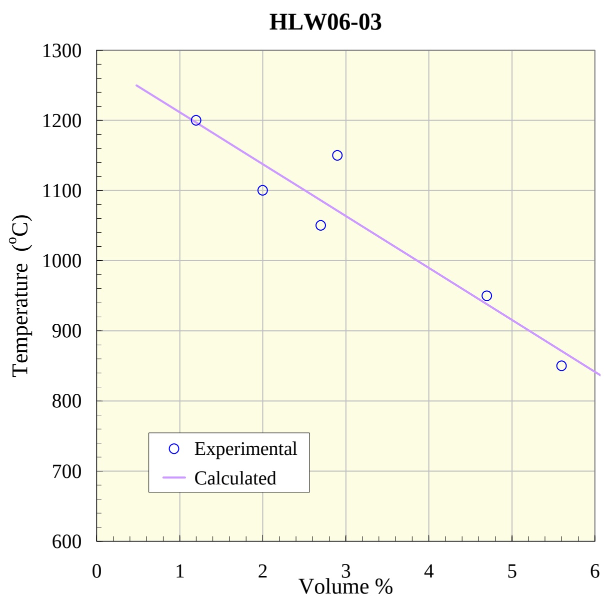


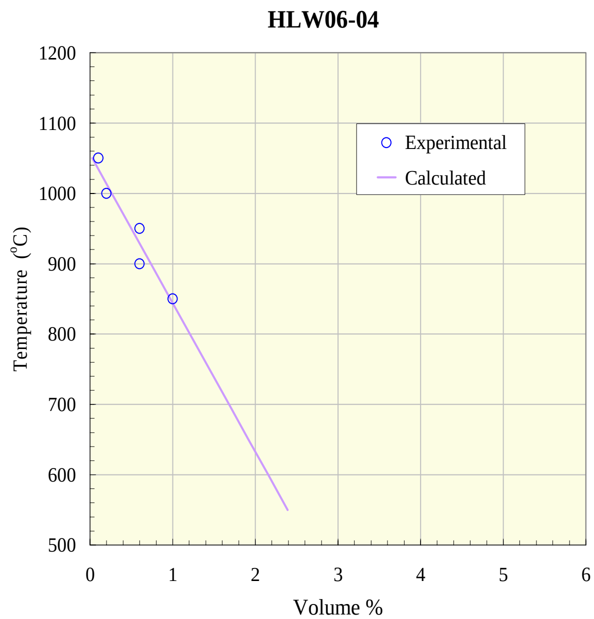


Note: Regression was not performed on the collected data

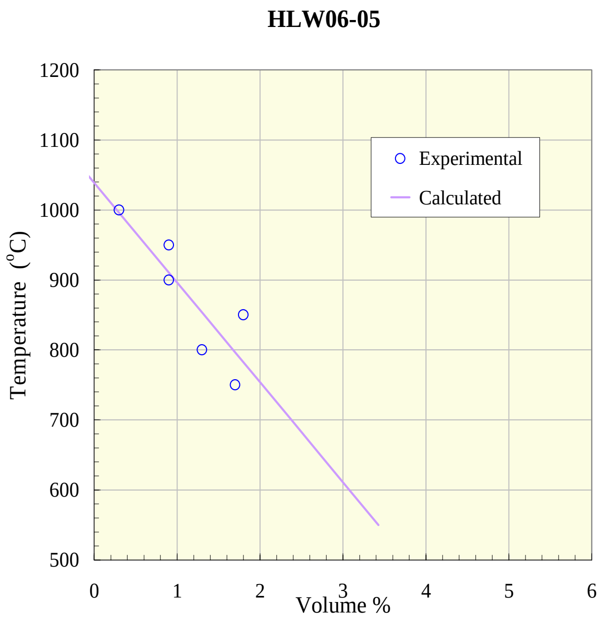


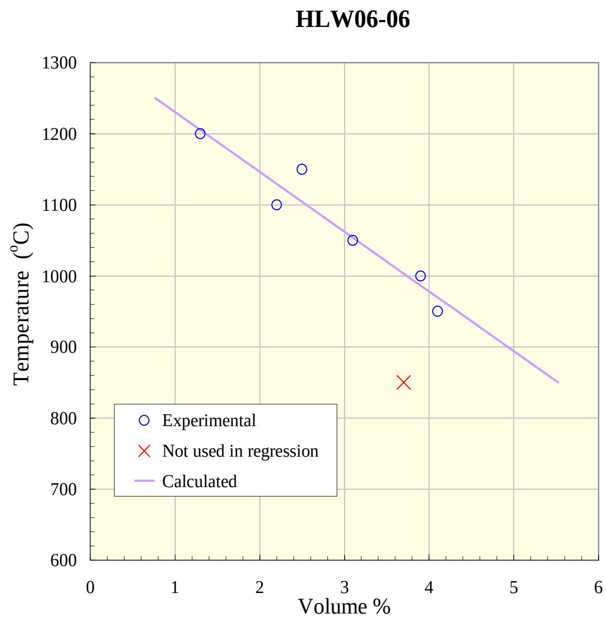


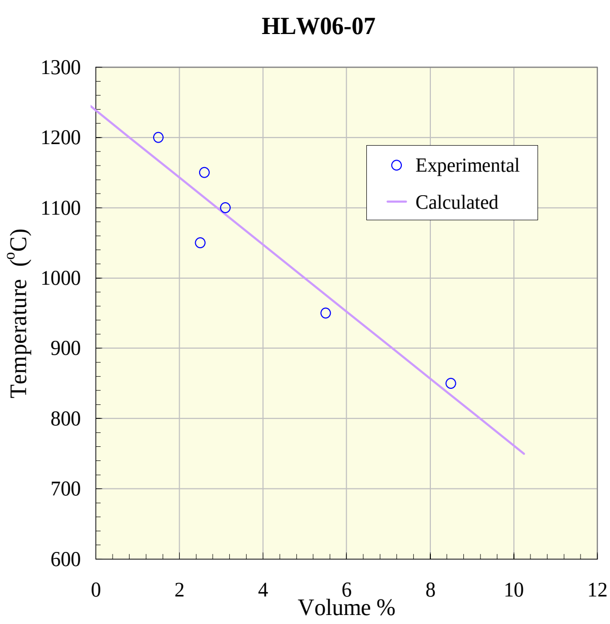


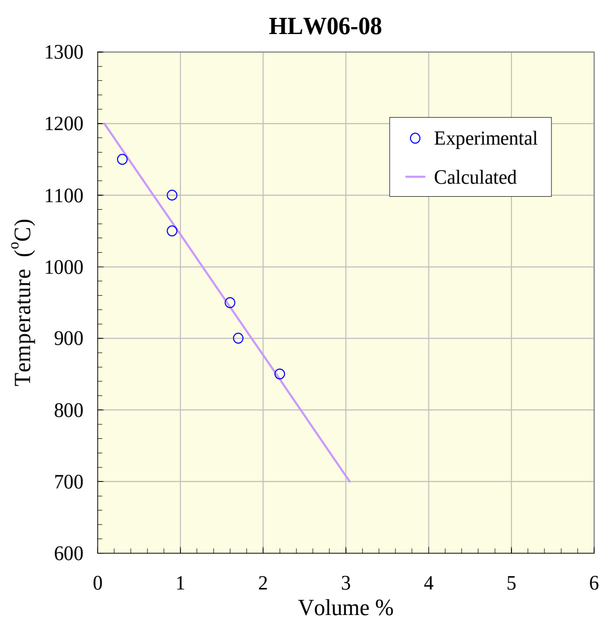


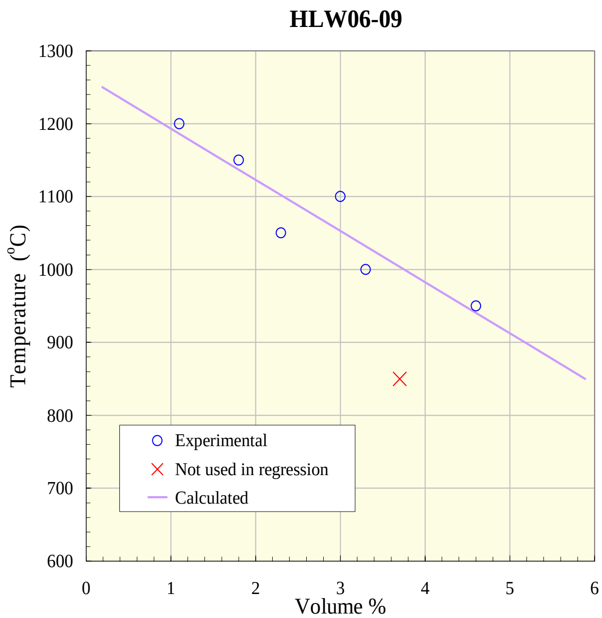
Note: Data point at (Vol % = 10.3, T = 750 °C) is not shown and was omitted from regression

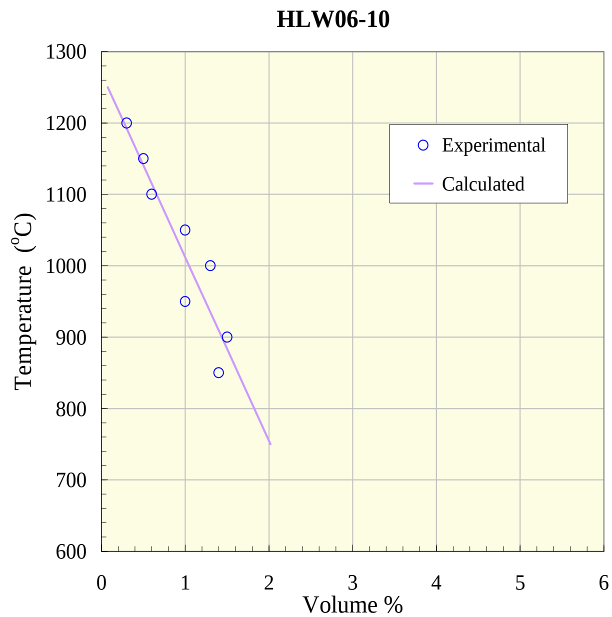

HLW06-05
Experimental
Calculated
Temperature (°C)
Volume %
1200
1100
1000
900
800
700
600
500
0
1
2
3
4
5
6

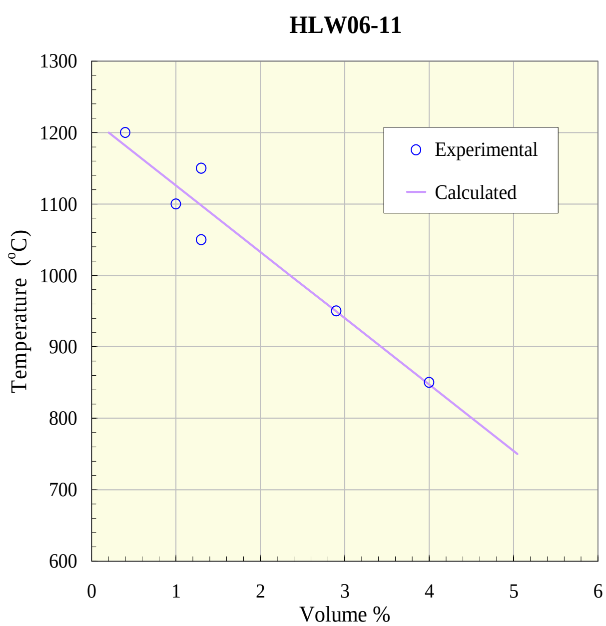

HLW06-06
Experimental
Not used in regression
Calculated
Temperature (°C)
Volume %
1300
1200
1100
1000
900
800
700
600
0
1
2
3
4
5
6

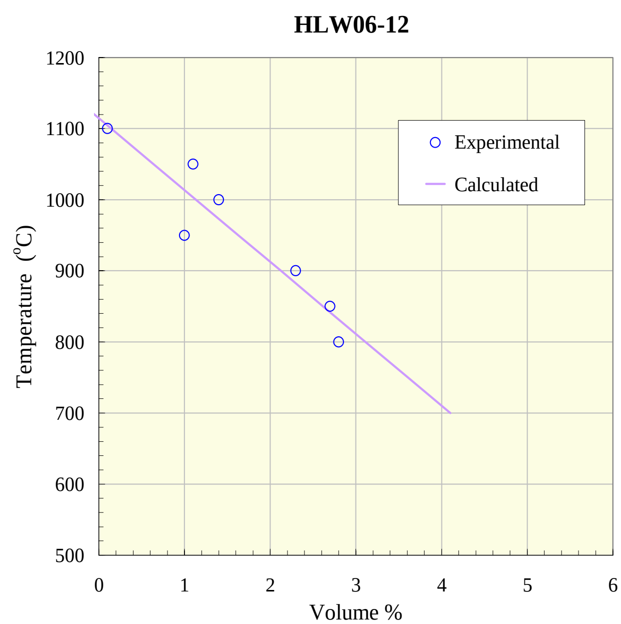

HLW06-07
Experimental
Calculated
Temperature (°C)
Volume %
1300
1200
1100
1000
900
800
700
600
0
2
4
6
8
10
12

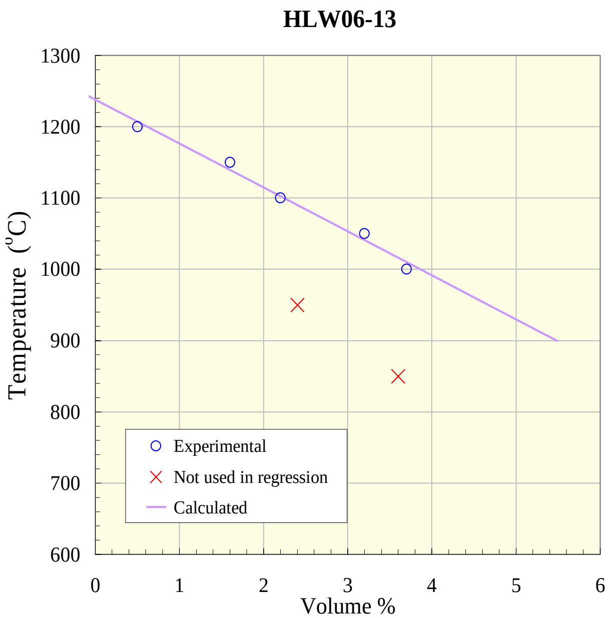

HLW06-08
Experimental
Calculated
Temperature (°C)
Volume %
1300
1200
1100
1000
900
800
700
600
0
1
2
3
4
5
6

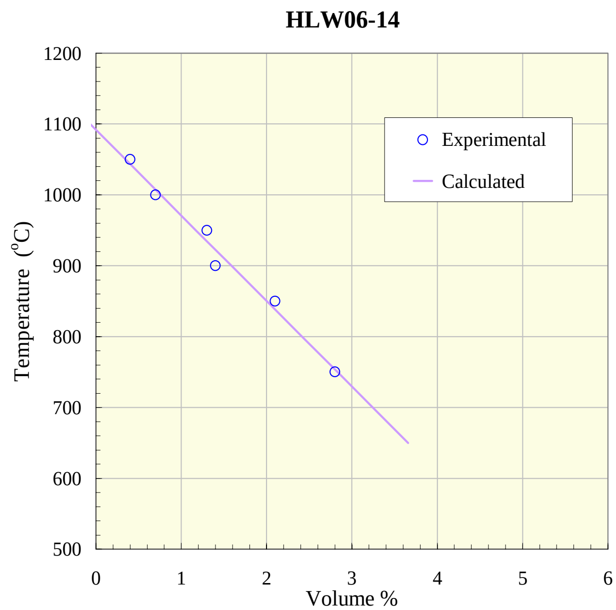

HLW06-09
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated

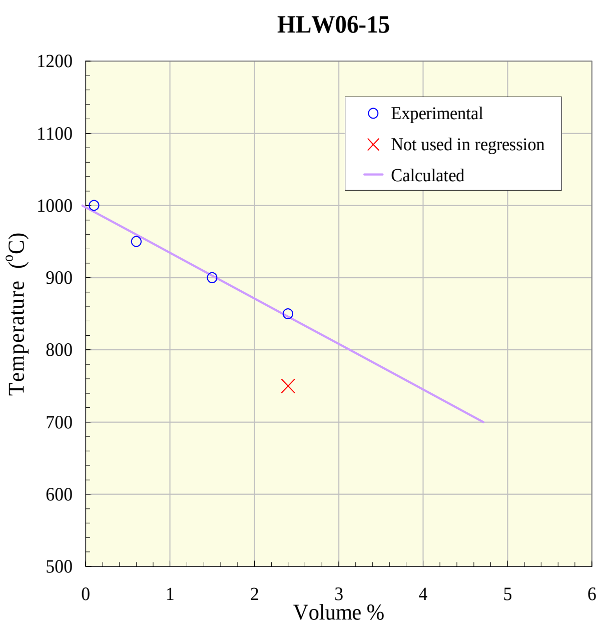

HLW06-10
Temperature (°C)
Volume %
Experimental
Calculated

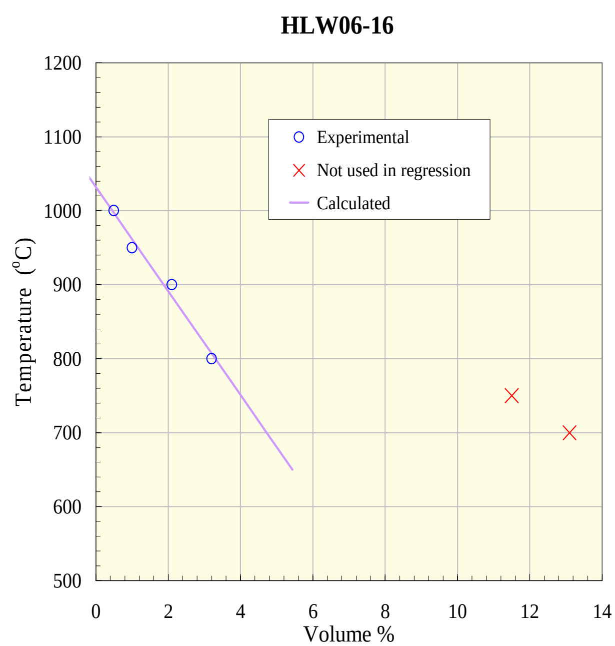

HLW06-11
Temperature (°C)
Volume %
Experimental
Calculated

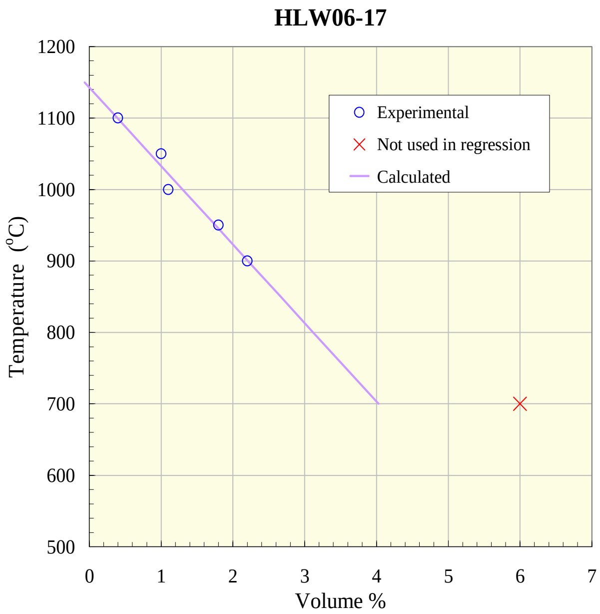

HLW06-12
Temperature (°C)
Volume %
Experimental
Calculated

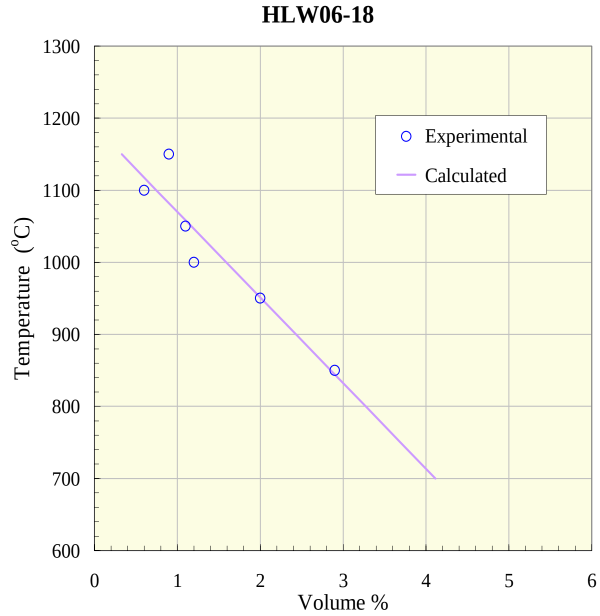

HLW06-13
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated

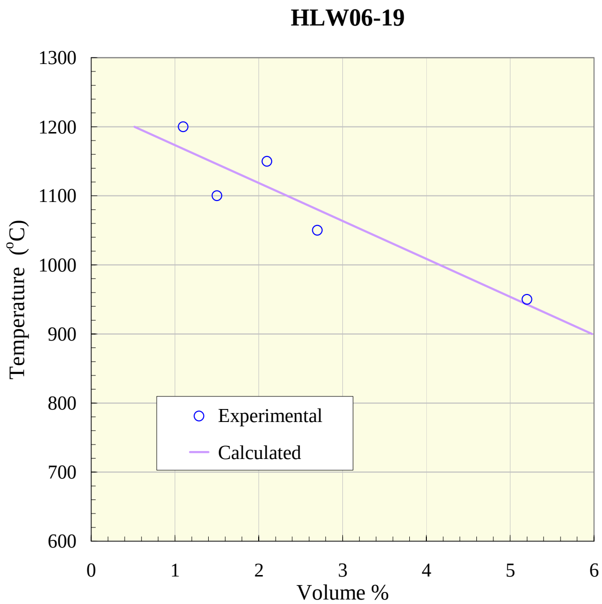

HLW06-14
Temperature (°C)
Volume %
Experimental
Calculated

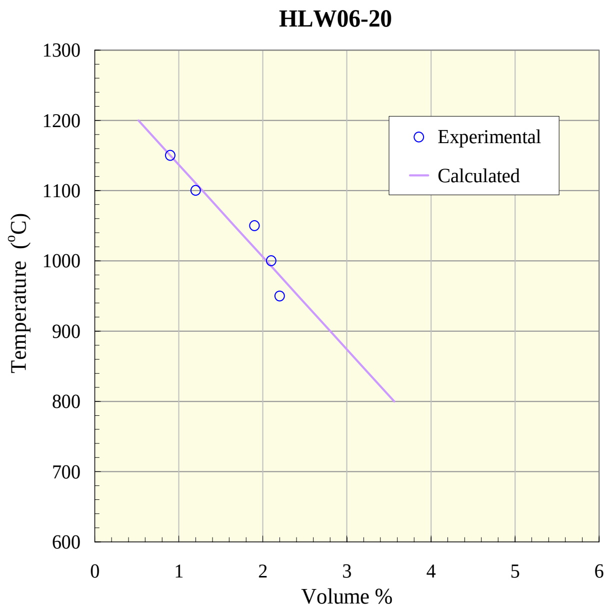

HLW06-15
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated


HLW06-16
Temperature (°C)
Volume %
Experimental
Not used in regression
Calculated

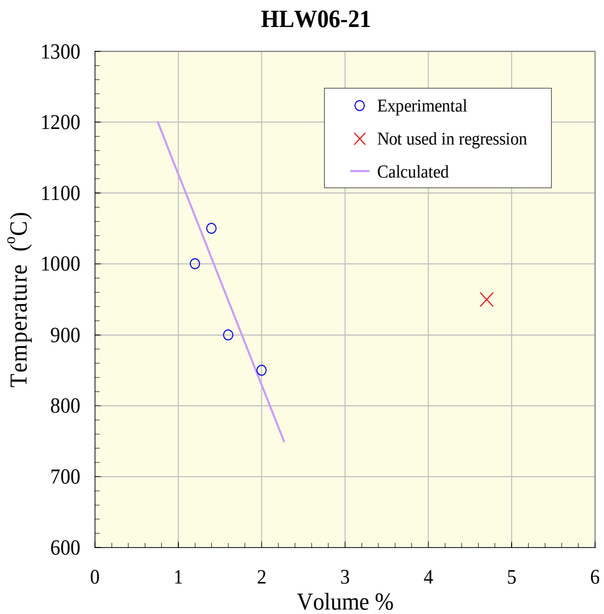




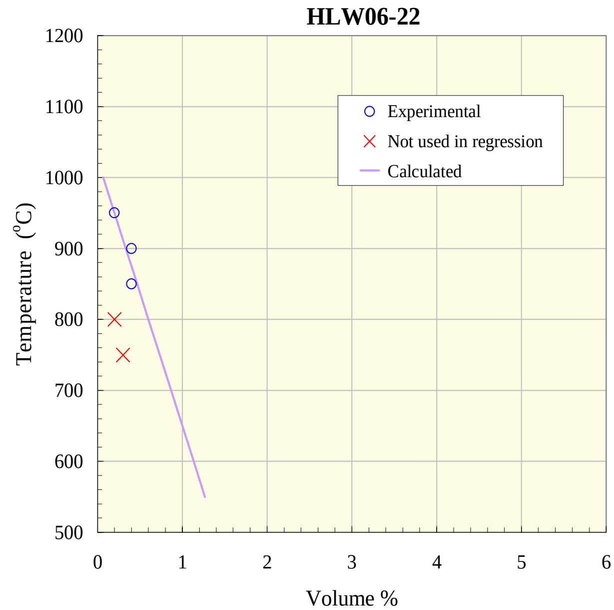


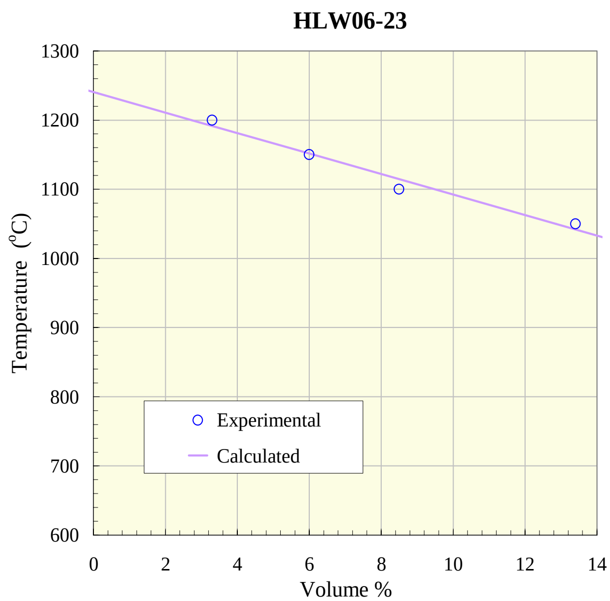


Note: Data point at (Vol % = 19.6, T = 750 °C) is not shown and was omitted from regression

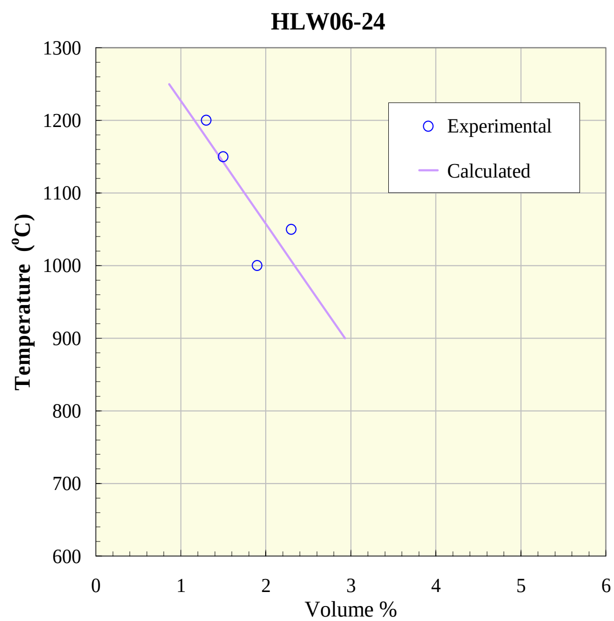


Note: Data point at (Vol % = 21.9, T = 750 °C) is not shown and was omitted from regression

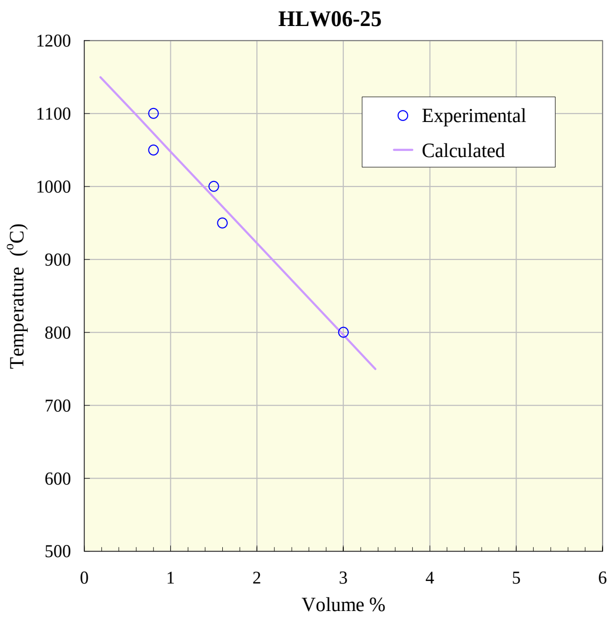


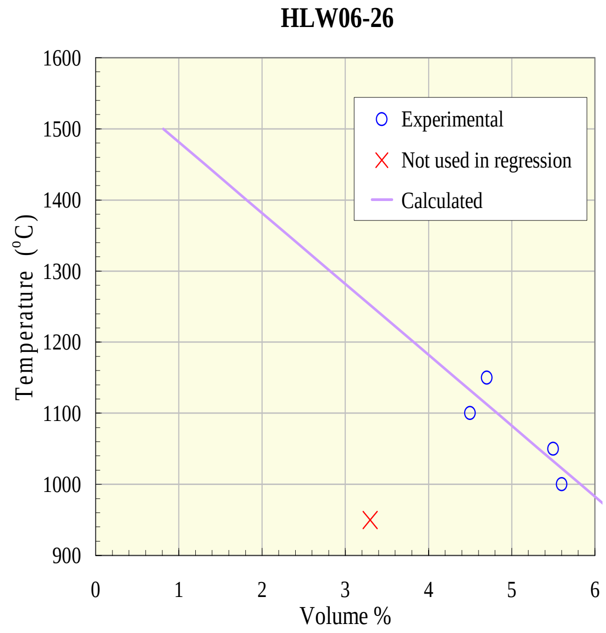


Note: Data point at (Vol % = 23.2, T = 950 °C) is not shown and was omitted from regression

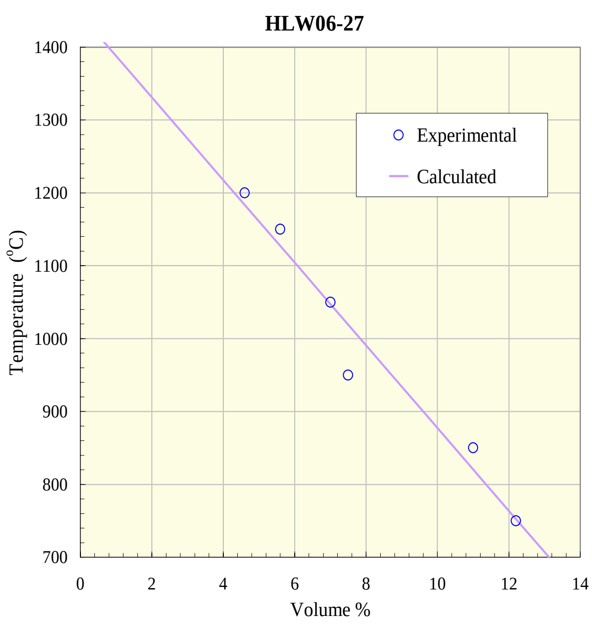


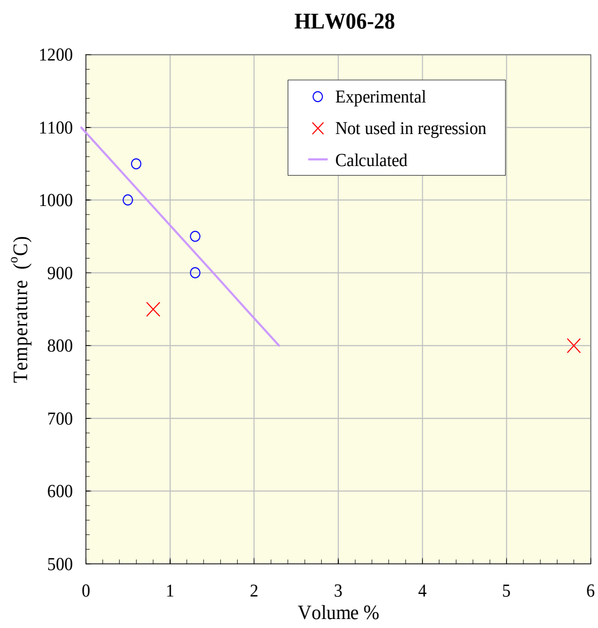
Note: Data points at (Vol % = 49.9, T = 750 °C), (Vol % = 41.5, T = 800 °C) and (Vol % = 28.6, T = 950 °C) are not shown and were omitted from regression

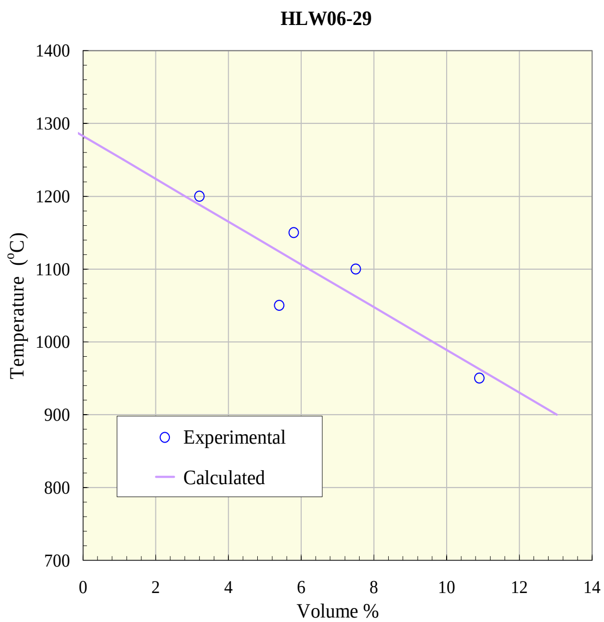




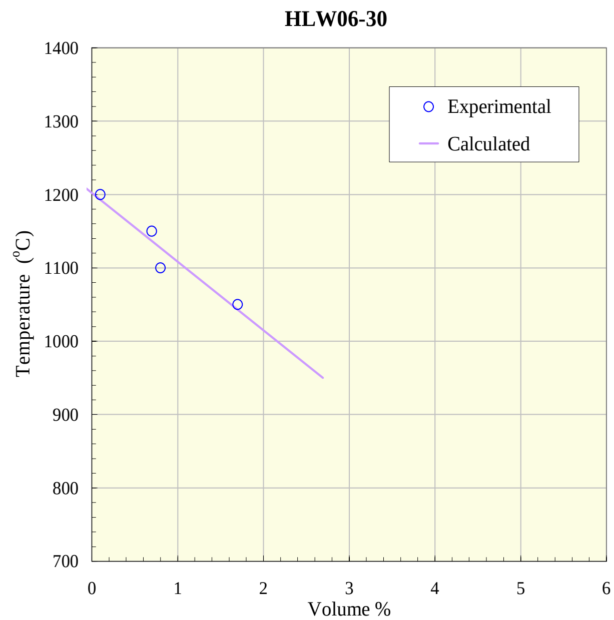
Note: Data points at (Vol % = 22.8, T = 750 °C) and (Vol % = 12.3, T = 850 °C) are not shown and were omitted from regression



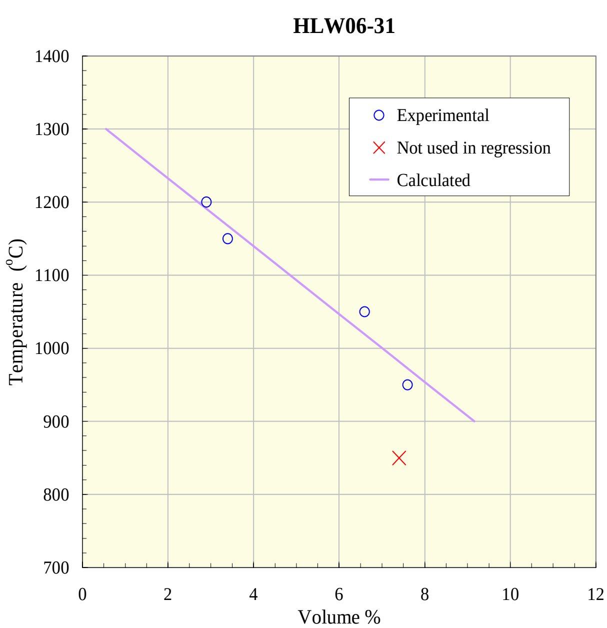


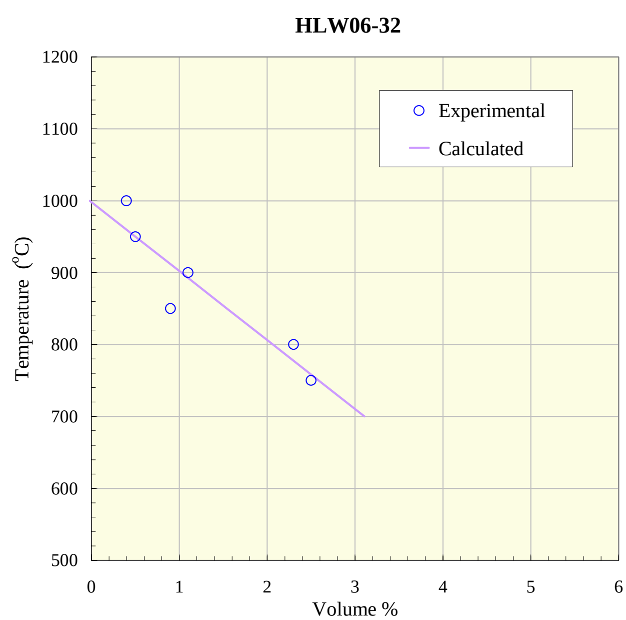


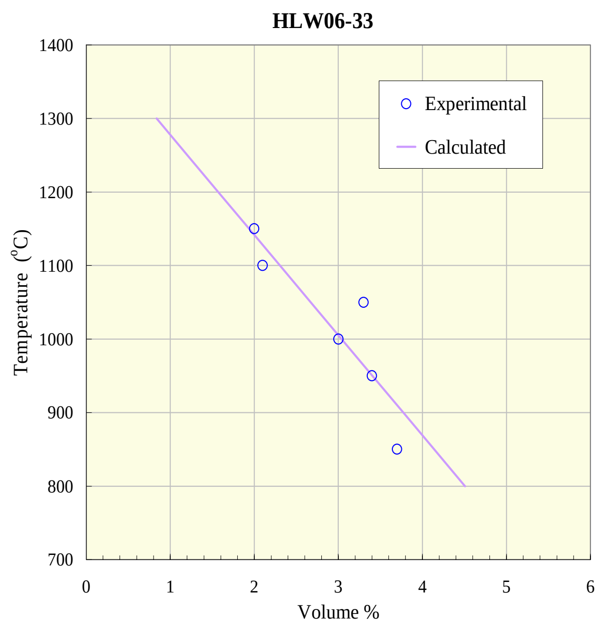
Note: Data point at (Vol % = 17.7, T = 850 °C) is not shown and was omitted from regression

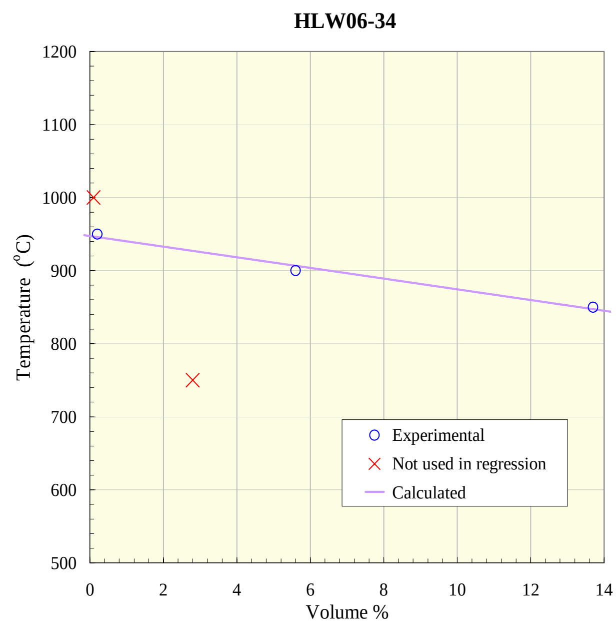


Note: Data points at (Vol % = 23.3, T = 850 °C) and (Vol % = 14.3, T = 950 °C) are not shown and were omitted from regression

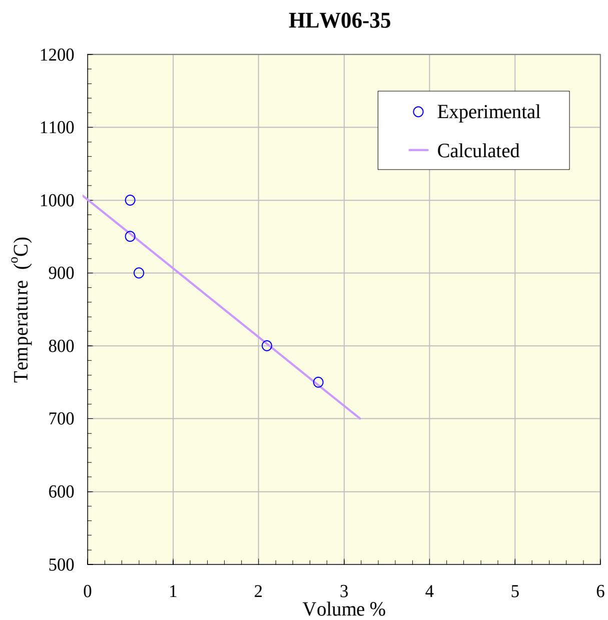








Note: Data point at (Vol % = 19.1, T = 750 °C) is not shown and was omitted from regression



R&T Subcontractor Document Review Record

1) To Be Completed by Cognizant R&T Personnel		
Document Number VSL-05R5780-2	Revision 0	Document Title Preparation and Testing of HLW Matrix Glasses to Support WTP Property-Composition Model Development Final Report
Test Spec: 24590-HLW-TSP-RT-01-006, Rev 1 24590-WTP-TSP--RT-02-001, Rev 0		Scoping Statement(s): VSL-13 HLW Glass Property Composition Modeling VSL-14 HLW Processing Properties Models

R&T Contact:	Keith Abel	MS6-N1	371-5847	8/31/05
	Name (Print)	MSIN	Telephone Number	Date

Review Distribution

Organization	Contact	MSIN	Required?
Process Operations	D McLaughlin	MS4-C1	Yes ☒ No ☐
Quality Assurance	M Mitchell	MS14-4A	Yes ☐ No ☒
Environmental and Nuclear Safety	E Sauceda	MS4-D2	Yes ☒ No ☐
Commissioning and Training	K Vacca	MS12-B	Yes ☐ No ☒
Engineering	M Ongpin	MS4-A2	Yes ☒ No ☐
R&T Functional Manager	J Perez	MS6-P1	Yes ☒ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐

Comments Due By: 9/14/05

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

2) To be Completed by Reviewer

Reviewer	David Blumenkranz	ENS	09/15/05
	Name (Print)	Organization	Date

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

3) To be Completed by Reviewer*

My significant comments have been addressed.

Acceptance:	David Blumenkranz	David Blumenkranz	09/15/05
	Print/Type Name	*Signature*	*Date*

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

Abel, Keith H.

From:	Blumenkranz, David
Sent:	Thursday, September 15, 2005 7:13 AM
To:	Abel, Keith H.
Cc:	Sauceda, Ermelinda
Subject:	Property-Composition Model Development Final Report

I concur with "*Preparation and Testing of HLW Matrix Glasses to Support WTP Property-Composition Model Development Final Report*" VSL-05R5780-2, Rev. 0

Dave Blumenkranz
WTP E&NS
(509) 371-3525
MS4-D1
MPF.2.D237

Abel, Keith H.

From: Blumenkranz, David
Sent: Thursday, September 08, 2005 11:21 AM
To: Abel, Keith H.
Subject: RE: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

No 'official' comments.

There's a typo in the heading row of Table 2.6 ("Contants").

-----Original Message-----
From: Abel, Keith H.
Sent: Wednesday, August 31, 2005 9:03 AM
To: Sauceda, Ermelinda; Mitchell, Michelle; Ongpin, Maria; Vacca, Karen; Mclaughlin, Doris
Cc: Bostic, Lee; Wells, Kenneth R; Reed, Ronald D; Gimpel, Rod; Eager, Kevin; Reynolds, Jacob; Kaiser, Bruce; Nelson, James L; Perez, Joseph; Lee, Ernest D (WTP); Fussner, Robert J; Vienna, John; Damerow, Frederick; Blumenkranz, David
Subject: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

I am requesting your assistance in review and finalization of the VSL draft report **Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-04R5780-2, Rev. A.** The Document Review Record Form, the Comment Resolution Form and an electronic version of the report are at the location shown below. I have also placed a copy of the Test Specifications, the Duratek/VSL Test Plan, and the Test Exception generated under the two scoping statements associated with the work in the folder on the R&T area on server wtps0166, linked below.

This report summarizes work at VSL, an additional report will be generated in the future that will describe utilization of the data for model development (a Battelle activity). This report summarizes glass preparation and testing activities in support of WTP Property-Composition Model Development conducted over the last year. The main objective is to augment the current data set and provide information to define the Phase 2 IHLW matrix for final PCT and T1% model development that will be conducted in the future. The effort is intended to improve models for the spinel matrix and provide an initial set of data to help define additional technical needs for Non-Spinel (high thorium or zirconium) model development

<\\wtps0166\R&T\HLW Formulation Support - Crystallinity Summary Report>

We appreciate your assistance in finalizing this document.

Comments are due no later than COB September 14, 2005

If you have any questions regarding this review request, please contact me (371-5847).

Please provide comments by e-mail back to me using the DRR and CRF located in the folder link above.

Thank you for your assistance in the review and finalization of this document.

Keith Abel
371-5847

RECEIVED
AUG 31 2005
By 16092

R&T Subcontractor Document Review Record

1) To Be Completed by Cognizant R&T Personnel		
Document Number	Revision	Document Title
VSL-05R5780-2	0	Preparation and Testing of HLW Matrix Glasses to Support WTP Property-Composition Model Development Final Report

Test Spec:	24590-HLW-TSP-RT-01-006, Rev 1 24590-WTP-TSP--RT-02-001, Rev 0	Scoping Statement(s):	VSL-13 HLW Glass Property Composition Modeling VSL-14 HLW Processing Properties Models

R&T Contact:	Keith Abel	MS6-N1	371-5847	8/31/05
	Name (Print)	MSIN	Telephone Number	Date

Review Distribution			
Organization	**Contact**	**MSIN**	**Required?**
Process Operations	D McLaughlin	MS4-C1	Yes ☒ No ☐
Quality Assurance	M Mitchell	MS14-4A	Yes ☐ No ☒
Environmental and Nuclear Safety	E Sauceda	MS4-D2	Yes ☒ No ☐
Commissioning and Training	K Vacca	MS12-B	Yes ☐ No ☒
Engineering	M Ongpin	MS4-A2	Yes ☒ No ☐
R&T Functional Manager	J Perez	MS6-P1	Yes ☒ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐

Comments Due By: 9/14/05

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

2) To be Completed by Reviewer

Reviewer	E SAUCEDA / PDC	ES/NS	9/15/05
	Name (Print)	Organization	Date

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

3) To be Completed by Reviewer*

My significant comments have been addressed.

Acceptance: ______________________ ______________________ ______________________
Print/Type Name *Signature* *Date*

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

-----Original Message-----
From: Abel, Keith H.
Sent: Wednesday, August 31, 2005 9:03 AM
To: Sauceda, Ermelinda; Mitchell, Michelle; Ongpin, Maria; Vacca, Karen; Mclaughlin, Doris
Cc: Bostic, Lee; Wells, Kenneth R; Reed, Ronald D; Gimpel, Rod; Eager, Kevin; Reynolds, Jacob; Kaiser, Bruce; Nelson, James L; Perez, Joseph; Lee, Ernest D (WTP); Fussner, Robert J; Vienna, John; Damerow, Frederick; Blumenkranz, David
Subject: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

I am requesting your assistance in review and finalization of the VSL draft report **Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-04R5780-2, Rev. A.** The Document Review Record Form, the Comment Resolution Form and an electronic version of the report are at the location shown below. I have also placed a copy of the Test Specifications, the Duratek/VSL Test Plan, and the Test Exception generated under the two scoping statements associated with the work in the folder on the R&T area on server wtps0166, linked below.

This report summarizes work at VSL, an additional report will be generated in the future that will describe utilization of the data for model development (a Battelle activity). This report summarizes glass preparation and testing activities in support of WTP Property-Composition Model Development conducted over the last year. The main objective is to augment the current data set and provide information to define the Phase 2 IHLW matrix for final PCT and T1% model development that will be conducted in the future. The effort is intended to improve models for the spinel matrix and provide an initial set of data to help define additional technical needs for Non-Spinel (high thorium or zirconium) model development

<\\wtps0166\R&T\HLW Formulation Support - Crystallinity Summary Report>

We appreciate your assistance in finalizing this document.

Comments are due no later than COB September 14, 2005

If you have any questions regarding this review request, please contact me (371-5847).

Please provide comments by e-mail back to me using the DRR and CRF located in the folder link above.

Thank you for your assistance in the review and finalization of this document.

Keith Abel
371-5847

Abel, Keith H.

From: Eager, Kevin
Sent: Thursday, September 15, 2005 8:14 AM
To: Abel, Keith H.
Subject: RE: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

"This means there are no comments from my area. "

Except for Scott Saunders group (e.g. Rod Gimpel as you said.

-----Original Message-----
From: Abel, Keith H.
Sent: Thursday, September 15, 2005 8:12 AM
To: Eager, Kevin
Subject: RE: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

Thank you.

Keith

-----Original Message-----
From: Eager, Kevin
Sent: Thursday, September 15, 2005 8:11 AM
To: Abel, Keith H.
Subject: FW: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

This means there are no comments from my area.

-----Original Message-----
From: Carl, Daniel
Sent: Thursday, September 15, 2005 8:10 AM
To: Eager, Kevin
Cc: Eaton, William; Larson, Andrew; Peters, Richard D (WTP)
Subject: RE: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

Kevin,

As input to the glass modeling effort, the document is outside the scope I have been reviewing. I have no comments.

Dan

-----Original Message-----
From: Eager, Kevin
Sent: Wednesday, September 14, 2005 3:23 PM
To: Carl, Daniel; Rouse, James
Subject: FW: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

Dan, Jim,

Could you take a quick look at this report and see if it's something you need to review.

Kevin Eager
371-3642

COMMENT RESOLUTION FORM

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
		data field.			clarification. The missing dashes will be added.	
13	Table 4.6	Temp of 750 for HLW05-18 does not have dash or data. Also would suggest change of italic text to bold as in Table 4.1 & 4.2, since it is much easier to identify bold in the table than italic type. Temp of 1100 for HLW05-26 has no data nor dash to indicate it should be empty.	E I E		The missing dash will be added. The suggested formatting change will be adopted. The missing dash will be added for HLW05-26.	
14	Table 4.7	Again suggest bold rather than italic text as in Table 4.6.	E		The suggested formatting change will be adopted.	
15	Table 4.8	Page T-32 the "outlining box" is not complete between the T1% entries for HLW05-26 & HLW05-27.	E		The appropriate border will be added.	
16	Table 4.9	Page T-33 the "outlining box" is not complete between the T1% entries for HLW05-26 & HLW05-27.	E		The appropriate border will be added.	
17	Table 4.10	The pooled standard deviation is for 6 replicate pairs of data, not 5 as stated, isn't it?	I		Yes, 6 replicate pairs were used to calculate the pooled standard deviation. The typo will be corrected.	

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

[b] Justification required for Mandatory Comments.

COMMENT RESOLUTION FORM

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
		Last Para, line 2 on page 26, the : should be ; near beginning of line. Last line in section on page 27; "modeling testing". Suggest change to "modeling tests".	E E		Suggested change will be made. Suggest change to "modeling tests" will be made.	
8	Sec 5	Para 2, last sentence. Suggest change to read: "Discrepancies for selected minor components........were traced to spectral interferences during analytical determination." Para 3, line 2 near end. : should be ; Para 3, 3rd line from end. See Item #1 last comment	I E I		Change will be made as suggested. While a semicolon is also used as a colon to mark a grammatical break in construction, a colon is more commonly used to introduce a series (unlike 3rd line on p. 25, see item 6). Suggested change will be made.	
9	Table 2.5	There are duplicate columns for B2O3 and Cr2O3. Delete duplication.	E		The duplication will be deleted.	
10	Table 2.6	Heading within the table has a typo. "Contant" should be "Constant"	E		The typo will be corrected.	
11	Table 4.1	Why not delete rows where there is no data in entire table, e.g., F, PdO, Sm2O3...	E		The empty rows were kept to facilitate copying of data from the source file and to avoid inadvertent mistakes during copying (some glasses have non-empty cells for these oxides).	
12	Table 4.2	Why not delete completely empty rows, e.g., Se2O3, MoO3, Ce2O3. Also, why the values of 0.00% for SeO2 and Y2O3 on page T-17? Also, SeO2 row on page T-18, T-19, & T-20 does not have data or dash to indicate empty	E E E		See response to item # 11. The values reported are rounded to 2 significant figures, with 0.00% indicating measurable amounts that are < 0.05%. A footnote will be added to provide	

COMMENT RESOLUTION FORM

Return to: Keith Abel

Comments Due: 9/14/05

Document Title:	Document No.	Revision:	Date:
Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development	VSL-05R5780-2	0	8/31/05

Reviewer:	Date:	Response by:	Date:	Comments Resolved:	Date:
Keith Abel	09/08/05			[signature]	9/30/05

Item No.	Section/ Paragraph	Comment	Significance[a]	"M" Comment Justification[B]	Response	Resolution
1	C) (Page 8)	Para 1, line 1 the word "a" should be deleted Para 2, line 6 near end "for modeling purpose" should be changed to read as stated on page 25, Para 1, 3rd line from end of para "for the purpose of model development"	E E		The word "a" will be deleted. Suggested change will be made.	
2	Sec 1	Line 1, "state" should be "State" since it is the "State of Washington"... Para 2, last line the word "of" after Phase 2 should be deleted.	E E		The suggested formatting change will be made. Deletion will be made as suggested.	
3	Sec 1.2	Line four on page 14 "make use of the collect data" should be "make use of the collected data"	E		Correction will be made as indicated.	
4	Sec 2.3	Last para, page 19, line 5, near end. Delete "on" from "greatly impact on various"	E		Suggested deletion will be made.	
5	Sec 4	Para 1, next to last line. Do not need comma after the close of the parentheses near end of line.	E		The sentence will be rewritten as follows: "… respectively). Section 4.3 also presents the one-percent …"	
6	Sec 4.2	3rd line on page 25. the : should be ; at end of line.	E		Change will be made as suggested.	
7	Sec 4.3	Line 2 at top of page 26; presents should be present.	E		Correction will be made as indicated.	

If you have any questions regarding this review request, please contact me (371-5847).

Please provide comments by e-mail back to me using the DRR and CRF located in the folder link above.

Thank you for your assistance in the review and finalization of this document.

Keith Abel
371-5847

Abel, Keith H.

From: Kaiser, Bruce
Sent: Monday, September 12, 2005 12:20 PM
To: Abel, Keith H.
Subject: RE: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

No comments beyond those that you have already discussed on the range of crystalinity.
Thanks
Bruce

-----Original Message-----
From: Abel, Keith H.
Sent: Monday, September 12, 2005 10:23 AM
To: Sauceda, Ermelinda; Mitchell, Michelle; Ongpin, Maria; Vacca, Karen; Mclaughlin, Doris
Cc: Wells, Kenneth R; Reed, Ronald D; Gimpel, Rod; Eager, Kevin; Reynolds, Jacob; Kaiser, Bruce; Nelson, James L; Perez, Joseph; Lee, Ernest D (WTP); Fussner, Robert J; Vienna, John
Subject: RE: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

All,

Just a note of reminder for those planning to comment on the above report. Your comments are due by COB Wednesday this week.

Thanks,

Keith

-----Original Message-----
From: Abel, Keith H.
Sent: Wednesday, August 31, 2005 9:03 AM
To: Sauceda, Ermelinda; Mitchell, Michelle; Ongpin, Maria; Vacca, Karen; Mclaughlin, Doris
Cc: Bostic, Lee; Wells, Kenneth R; Reed, Ronald D; Gimpel, Rod; Eager, Kevin; Reynolds, Jacob; Kaiser, Bruce; Nelson, James L; Perez, Joseph; Lee, Ernest D (WTP); Fussner, Robert J; Vienna, John; Damerow, Frederick; Blumenkranz, David
Subject: Document Review: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-05R5780-2, Rev. 0

I am requesting your assistance in review and finalization of the VSL draft report **Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development, VSL-04R5780-2, Rev. A.** The Document Review Record Form, the Comment Resolution Form and an electronic version of the report are at the location shown below. I have also placed a copy of the Test Specifications, the Duratek/VSL Test Plan, and the Test Exception generated under the two scoping statements associated with the work in the folder on the R&T area on server wtps0166, linked below.

This report summarizes work at VSL, an additional report will be generated in the future that will describe utilization of the data for model development (a Battelle activity). This report summarizes glass preparation and testing activities in support of WTP Property-Composition Model Development conducted over the last year. The main objective is to augment the current data set and provide information to define the Phase 2 IHLW matrix for final PCT and T1% model development that will be conducted in the future. The effort is intended to improve models for the spinel matrix and provide an initial set of data to help define additional technical needs for Non-Spinel (high thorium or zirconium) model development

<\\wtps0166\R&T\HLW Formulation Support - Crystallinity Summary Report>

We appreciate your assistance in finalizing this document.

Comments are due no later than COB September 14, 2005

Abel, Keith H.

From: Abel, Keith H.
Sent: Friday, September 30, 2005 1:19 PM
To: Valenti, Thomas
Subject: FW: Comment Resolution for VSL-05R5780-2, Prep & Testing (T1% & PCT) of HLW Matrix Glasses to Support Prop Comp Models

Tom,

Attached, for your records, is the electronic copy of the comments Rod has signed off on in hardcopy a few minutes ago. I would appreciate Engineering concurrence for proceeding to Rev 0 for this document, since Rod was the only Engineering reviewer to provide comment on the draft.

Thanks,

Keith

-----Original Message-----
From: Abel, Keith H.
Sent: Friday, September 30, 2005 10:52 AM
To: Gimpel, Rod
Subject: Comment Resolution for VSL-05R5780-2, Prep & Testing (T1% & PCT) of HLW Matrix Glasses to Support Prop Comp Models

Rod,

Attached are VSL's proposed resolutions for your comment on the above report. Please review and let me know if the responses resolve your comments.

Thanks,

Keith Abel

comres gimpel.doc

R&T Subcontractor Document Review Record

1) To Be Completed by Cognizant R&T Personnel		
Document Number VSL-05R5780-2	Revision 0	Document Title Preparation and Testing of HLW Matrix Glasses to Support WTP Property-Composition Model Development Final Report
Test Spec: 24590-HLW-TSP-RT-01-006, Rev 1 24590-WTP-TSP--RT-02-001, Rev 0		Scoping Statement(s): VSL-13 HLW Glass Property Composition Modeling VSL-14 HLW Processing Properties Models

R&T Contact:	Keith Abel	MS6-N1	371-5847	8/31/05
	Name (Print)	MSIN	Telephone Number	Date

Review Distribution

Organization	Contact	MSIN	Required?
Process Operations	D McLaughlin	MS4-C1	Yes ☒ No ☐
Quality Assurance	M Mitchell	MS14-4A	Yes ☐ No ☒
Environmental and Nuclear Safety	E Sauceda	MS4-D2	Yes ☒ No ☐
Commissioning and Training	K Vacca	MS12-B	Yes ☐ No ☒
Engineering	M Ongpin	MS4-A2	Yes ☒ No ☐
R&T Functional Manager	J Perez	MS6-P1	Yes ☒ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐
			Yes ☐ No ☐

Comments Due By: 9/14/05

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

2) To be Completed by Reviewer

Reviewer	Tom Valenti for Jerry Chiaramonte	Process Engineering	9/30/05
	Name (Print)	Organization	Date

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

3) To be Completed by Reviewer*

My significant comments have been addressed.

Acceptance: ______________ ______________ ______________

Print/Type Name *Signature* *Date*

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

Thank you for your assistance in the review and finalization of this document.

Keith Abel
371-5847

Process Engineering has completed its review and does not have mandatory comments. Editorial comments have been provided separately by Rod Gimpel and Jacob Reynolds. SDRR is attached.

« File: Rev Rec VSL HLW Glasses Comp rept.doc »

Thomas J. Valenti

Process Engineering Group
MPF C120A
509/ 371-3760

-----Original Message-----
From: Eager, Kevin
Sent: Wednesday, September 14, 2005 9:31 AM
To: Carl, Daniel; Rouse, James
Cc: Mclaughlin, Doris
Subject: FW: Document Review: VSL-05R5760-1, Comparison of HLW Simulant, Actual Waste, and Melter Glasses, Rev 0

-----Original Message-----
From: Abel, Keith H.
Sent: Tuesday, September 13, 2005 10:06 AM
To: Sauceda, Ermelinda; Mitchell, Michelle; Ongpin, Maria; Vacca, Karen; Mclaughlin, Doris
Cc: Reed, Ronald D; Bostic, Lee; Wells, Kenneth R; Damerow, Frederick; Vienna, John; Gimpel, Rod; Reynolds, Jacob; Kaiser, Bruce; Nelson, James L; Perez, Joseph; Macpherson, David; Lee, Ernest D (WTP); Fussner, Robert J; Eager, Kevin; Damerow, Frederick
Subject: Document Review: VSL-05R5760-1, Comparison of HLW Simulant, Actual Waste, and Melter Glasses, Rev 0

All,

I am requesting your assistance in review and finalization of the VSL draft report **VSL-05R5760-1, Comparison of HLW Simulant, Actual Waste, and Melter Glasses, Rev. A.** The Document Review Record Form, the Comment Resolution Form and an electronic version of the report are at the location shown below. I have also placed a copy of the Test Specifications and the Duratek/VSL Test Plans generated under the scoping statements associated with the work in the folder on the R&T area on server wtps0166, linked below.

This report summarizes work at VSL for IHLW. The report summarizes glass formulation activities in support of WTP conducted to date. The main objective is to compare the compositions and properties of simulant crucible melts, actual radioactive waste melts, and melter glasses to demonstrate that glasses of similar compositions have similar properties, irrespective of the preparation methods and scale of production, or whether they are made from simulant or actual wastes.

<\\wtps0166\R&T\Comparison of HLW Simulant Actual waste and Melter Glasses Rept>

We appreciate your assistance in finalizing this document.

Comments are due no later than COB September 27, 2005

If you have any questions regarding this review request, please contact me (371-5847).

Please provide comments by e-mail back to me using the DRR and CRF located in the folder link above.

Abel, Keith H.

From: Valenti, Thomas
Sent: Monday, October 03, 2005 9:13 AM
To: Valenti, Thomas; Abel, Keith H.
Cc: Ongpin, Maria; Mclaughlin, Doris; Tsang, Irving
Subject: RE: Document Review: VSL-05R5780-2, Prep & Testing (T1% & PCT) of HLW Matrix Glasses to Support Prop Comp Models

The subject for the previous email is not correct. This email corrects the subject line and resends the attachment, corresponding with the SDRR. Sorry for any confusion.

Doc Rev Rec
5L05R5780-2 R0.do.

Thomas J. Valenti

Process Engineering Group
MPF C120A
509/ 371-3760

-----Original Message-----
From: Valenti, Thomas
Sent: Monday, October 03, 2005 9:04 AM
To: Abel, Keith H.
Cc: Ongpin, Maria; Mclaughlin, Doris; Tsang, Irving; Valenti, Thomas
Subject: RE: Document Review: VSL-05R5760-1, Comparison of HLW Simulant, Actual Waste, and Melter Glasses, Rev 0

Attached is the completed SDRR for process engineering.
« File: Doc Rev Rec VSL05R5780-2 R0.doc »

Thomas J. Valenti

Process Engineering Group
MPF C120A
509/ 371-3760

-----Original Message-----
From: Valenti, Thomas
Sent: Wednesday, September 28, 2005 8:44 AM
To: Abel, Keith H.
Cc: Mclaughlin, Doris; Tsang, Irving
Subject: RE: Document Review: VSL-05R5760-1, Comparison of HLW Simulant, Actual Waste, and Melter Glasses, Rev 0

R&T Technology Issues Summary

Test Report Title: Preparation and Testing (T1% and PCT) of HLW Matrix Glasses to Support WTP Property-Composition Model Development

Test Report Number: VSL-05R5780-2, Rev 0

Prepared By: Keith Abel **Date:** October 13, 2005

Signature: [signature]

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

If yes, describe the suggested activity.

This report describes sample preparation and testing work at VSL in support of IHLW PCT crystal fraction temperature model development. This report contains data to further support initial models where spinel is the expected dominant crystalline phase and an initial set of glasses where crystalline phases other then spinel are expected to dominate, e.g., AY-101/C-104. The model development and refinement is the second follow-on step in the overall activity and will be reported in another document. Finally, additional testing and model development activities are planned to support glasses where crystalline phases other than spinel will dominate. The work to further extend the models for non-spinel phases is being conducted during a Phase 2 activity.

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

Additional comments (include researcher recommendations):