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UC-~~512~~ 2030
Project Technical Information

Evaluation of Phase II Glass Formulations for Vitrification of Hanford Site Low-Level Waste

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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
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Summary

A vendor glass formulation study was carried out at Pacific Northwest Laboratory (PNL), supporting the Phase I and Phase II melter vendor testing activities for Westinghouse Hanford Company. This study is built upon the LLW glass optimization effort that will be described in a separate report. For Phase I vendor melter testing, six glass formulations were developed at PNL and additional glasses were developed by Phase I vendors. All the glasses were characterized in terms of viscosity and chemical durability by the 7-day Product Consistency Test. Twelve Phase II glass formulations (see Tables 3.5 and 3.6) were developed to accommodate 2.5 wt% P_2O_5 and 1.0 wt% SO_3 without significant processing problems. These levels of P_2O_5 and SO_3 are expected to be the highest possible concentrations from Hanford Site LLW streams at 25 wt% waste loading in glass. The Phase II compositions formulated were 6 to 23 times more durable than the environmental assessment (EA) glass. They melt within the temperature range of 1160° to 1410°C to suit different melting technologies. The composition types include boron-free glasses for volatilization sensitive melters; boron-containing glasses for cold-cap melters; Zr-containing glasses for enhanced long-term durability; and Fe-containing glasses for reducing melting temperature and melt volatility while maintaining chemical durability. Glasses made from simulated waste slurries were more prone to foaming and phase segregation than were glasses prepared from dry chemicals, especially those with high sulphur and phosphorus content. Surprisingly, glasses prepared from slurries were more oxidized, i.e., had lower Fe(II)/(Total Fe) ratios, and had higher solubilities of sulphur. The glasses made from dry chemicals and slurries had similar chemical durabilities, viscosities, and phosphorus solubilities. The Phase II formulations were also demonstrated to be able to incorporate a total 3 wt% of Cu, Zn, Pb, Sn, Cr, Mn, Ni, Mo, Sb, As, Bi, and Cd although these metal-containing glasses were slightly less durable.

1.0 Introduction

1.1 Background

The 230,000 m^3 of radioactive defense wastes stored in 177 underground single-shell tanks (SST) and double-shell tanks (DST) at the Hanford Site will be separated into low-level and high-level fractions. The Tri-Party Agreement (TPA) between the State of Washington Department of Ecology, the U.S. Department of Energy, and the U.S. Environmental Protection Agency specifies vitrification as the immobilization method for Hanford Site low-level waste (LLW) (TPA 1993). The reference melter technology and glass will be selected by June 1996, according to this agreement.

A multi-phase melter-systems technology demonstration, testing, and evaluation program is underway to identify the best overall melter-system technology available for vitrification of Hanford Site LLW to meet the TPA milestones (Wilson 1995). Phase I is a "proof of principle" test to demonstrate that a melter system can process a simulated highly alkaline, high nitrate/nitrite content aqueous LLW feed and produce a glass product of consistent quality. Seven melter vendors were selected for the Phase I evaluation, as follows: Joule-heated melters from GTS Duratek, Incorporated (GDI); Envitco, Incorporated (EVI); Penberthy Electromelt, Incorporated (PEI); and Vectra Technologies, Incorporated (VTI); gas-fired cyclone burner from Babcock & Wilcox (BCW); plasma torch-fired, cupola furnace from Westinghouse Science and Technology Center (WSTC); and electric arc furnace with top-entering vertical carbon electrodes from U.S. Bureau of Mines (UBM).

Phase II evaluations will allow for more comprehensive testing of equipment and procedures for selected promising technologies. Melter capability for handling wastes with high contents of F, Cl, P, and S will be tested. Melter systems with the greatest flexibility to process feeds with these components will be identified. Data will indicate concentration limits for these components that can be realistically processed by vitrification. At the end of Phase II, a preferred and a backup technology will be selected by Westinghouse Hanford Company (WHC).

Because durability and performance requirements for Hanford Site LLW glasses have not yet been established, flexibility in melting temperature and the capability of processing a range of glass compositions are the key factors in melter system technology selection. The high content of Na_2O in the Hanford Site LLW, averaging about 80 wt% on an oxide basis, necessitates the development of

durable high-sodium glasses. Vendors were required to use a "reasonable" LLW glass formulation for testing. Two criteria were established for the glass formulations (Wilson 1995): 1) waste oxide loading of LLW simulant in the glass should be approximately 25 wt% (about 20 wt% of Na_2O in glass); and 2) the glass should have a normalized Na release rate of 7 g/m^2/7-day or less, measured by the product consistency test (PCT) method (Jantzen 1992) at 90°C. This is the approximate durability of the Environmental Assessment glass that is used as a minimum durability benchmark for high-level waste (HLW) glass.

Pacific Northwest Laboratory (PNL) is providing glass formulation support for this program. Melter vendors could select the glasses from the formulations provided by PNL or they were free to develop their own glass compositions, provided the glass meet the two aforementioned criteria. Glasses adopted by vendors were also tested at PNL to verify the required properties. Testing included durability evaluation through PCT, viscosity measurements, and composition analysis.

1.2 Objectives

The objective of this work is to provide formulation, testing, and evaluation of candidate glasses to support a successful melter technology evaluation to be conducted by WHC for vitrification of Hanford Site LLW. The specific activities conducted include the following:

- provide proper formulations for Phase I and Phase II melter testing
- determine the solubility limits of F, Cl, P, S, and Cr in LLW glasses and develop optimized composition to increase solubility of these minor components, while maintaining the required processability and chemical durability
- evaluate glasses generated by vendors through durability testing, viscosity measurement, and composition analysis.

1.3 Approach

1.3.1 Considerations

The most important considerations for acceptable LLW waste glass compositions are the capability to incorporate high sodium content from LLW; satisfactory long-term durability; and proper processability, such as the capability of achieving the desired viscosity at melting temperature.

1.3.2 Chemical Durability

Long-term durability requirements and the link between short-term laboratory tests and long-term durability have not been established (McGrail 1992). However, a three-stage-corrosion mechanism of typical silicate glasses in aqueous media is generally accepted (Cunnane 1994). The initial stage under solution-dominated condition (dilute solution) is characterized by a forward reaction rate; that is, the maximum rate achievable depends only on glass composition, temperature, and solution pH. In the intermediate stage, glass reaction rate continuously decreases as the concentration of elements released from the glass in the solution increases. The final stage of enhanced glass corrosion begins when secondary mineral phases precipitate from the concentrated or "saturated/over-saturated" solution. The precipitation of mineral phases causes the solution to become less concentrated and the glass reaction affinity increases.

Glass development demands testing many glasses in a short time; it is not practical to perform long-term durability tests on every glass. The current chemical durability approach focuses on a suite of short-term laboratory tests, such as dynamic flow-through tests (McGrail 1992), static PCT tests (Jantzen 1992), and vapor hydration tests (Bates 1982).

The static PCT tests are to provide information about the second stage of glass reaction, which includes the lowest rate attainable before secondary phase formation. These tests couple solution chemistry and glass corrosion. Static PCT includes tests under standard test conditions (at 2000/m and 90°C for 7 days) and under extended conditions such as 20,000/m and longer test durations. The LLW glass optimization program uses PCT tests under both types of conditions. Only the results from the standard conditions are discussed here. The results from extended test conditions will be discussed in a future report.

The dynamic flow-through test provides the glass forward-reaction rate, the maximum corrosion rate of a glass composition at a given temperature and solution pH. This is a single-path flow-through (SPFT) test under controlled chemical conditions, including pH and temperature. Constant chemical conditions are attained by flowing buffer solution through the system at high flow-rates. Controlled environmental test conditions allow for the determination of key parameters (such as the intrinsic rate constant and power law coefficients) required for modelling the dissolution kinetics of silicate glasses or minerals. In traditional static leach tests, these parameters cannot be determined because the chemical affinity and pH change over the course of the test. The conditions of the flow-through test are meant to keep the leachant under saturated to eliminate precipitation effects and to maintain a constant pH. The results of this test (obtained from leachant samples taken as a function of time) should provide supplementary performance assessment information to model the kinetics of dissolution of various waste forms adequately.

1.3.3 Melter Technology

Until recently, nuclear waste vitrification developers focused on low-temperature melters ($\leq$1150°C). Glasses for such melters are mainly borosilicates. However, various glass-melting technologies available in the commercial glass industry have been further developed for waste vitrification. The high-temperature melters ($\geq$1250°C) attempt to match commercial glass melters in their capabilities of processing glass at a high melting rate and reducing waste form volume by allowing the waste loading to increase above that of low-temperature glasses.

The large range of melting temperatures available for the melters being evaluated precludes development of any single glass composition that could be used for all melter vendors. The Phase I vendor glasses research focused on high-temperature glasses with melting temperatures (at viscosity = 10 Pa.S) between 1290° and 1380°C. The Phase II glasses were developed for temperatures between 1150° and 1420°C.

1.3.4 Waste Loading and Compositions

Reasonable chemical durability can be obtained with aluminosilicate glasses at 20 wt% sodium content (Kim 1994). Such sodium loading gives a practical and reasonable 25 wt% dry-solid loading of Hanford Site LLW. The glass development effort has been focusing on compositions at 20 wt%

Na_2O. This waste loading can be adjusted in the future depending on future decisions concerning glass performance and waste volume reduction requirements.

Two waste simulants were provided for the Phase I vendor test. The first waste simulant was based on the analysis of six tanks of double-shelled slurry feed (DSSF) waste and on the projected composition of the wastes exiting the pretreatment operation (Shade 1994). The second LLW stream simulant, referred to as the remaining inventory (RI), included wastes not included in the DSSF tanks and the projected LLW fraction of single-shell tank wastes (Shade 1994). Only the DSSF waste simulant was used in the Phase I vendor testing. The waste compositions are shown in Table 1.1.

Two compositions of LLW simulants, modified DSSF (M-DSSF) and modified RI (M-RI), were provided for use in Phase II melter vendor tests (Shade 1995). The modified DSSF simulants were spiked with Cl and F at levels which would result in concentrations at their solubility limit in normal silicate glasses, based on a 25 wt% waste oxide-loading in the glass. The simulant contained concentrations of F and Cl at four times their solubility in glasses. Similarly, the modified RI contained four times the solubility of P_2O_5 and SO_3. The compositions used in the Phase II vendor glass formulations were shown in Table 1.1.

The nominal LLW composition shown in Table 1.1 represents the average composition of all tank wastes except those included in the DSSF. The simulated nominal LLW composition (NLLW) was used in glass formulation activities except Phase I and Phase II vendor glass studies.

Table 1.1. Compositions of LLW Waste Simulants (wt%)

	NLLW	DSSF	M-DSSF	M-RI
SiO2	0.03			
Na2O	84.42	76.05	74.02	78.93
CaO	0.01	0.01	0.01	0.01
Al2O3	6.19	12.20	11.69	3.46
Others	9.35	11.74	14.28	17.59
Others Components				
Bi2O3	0.06			
Cr2O3	0.15	0.15	0.15	0.14
Cs2O		0.56*	0.53*	0.60*
Fe2O3	0.02	0.01	0.01	0.01
K2O	1.38	5.54	5.31	0.12
MgO		0.01	0.01	
MnO	0.03	0.01	0.01	0.04
MoO3		0.57*	0.54*	0.61*
Nd2O3	0.05			
SrO		0.40*	0.38*	0.44*
ZrO2	0.02			
P2O5	5.01	0.72	0.69	9.95
SO3	1.35	0.82	0.78	3.98
Cl	0.39	1.33	2.38	0.14
F	0.90	1.12	3.02	1.04
I		0.50*	0.47*	0.54*

* These elements were spiked to increase the concentration so that mass balance across the melter during melter evaluation tests can be determined.

1.3.5 Glass Systems

The following aluminosilicate systems were considered for the development of vendor glasses:

Na_2O-Al_2O_3-B_2O_3-SiO_2
Na_2O-Al_2O_3-CaO-SiO_2
Na_2O-Al_2O_3-CaO-B_2O_3-SiO_2
Na_2O-Al_2O_3-Fe_2O_3-SiO_2
Na_2O-Al_2O_3-B_2O_3-ZrO_2-SiO_2
Na_2O-Al_2O_3-B_2O_3-Fe_2O_3-SiO_2
Na_2O-Al_2O_3-CaO-ZrO_2-SiO_2
Na_2O-Al_2O_3-CaO-Fe_2O_3-SiO_2
Na_2O-Al_2O_3-CaO-B_2O_3-ZrO_2-Fe_2O_3-SiO_2

These glass systems were evaluated for chemical durability, processability (viscosity and devitrification behavior), and the capability to incorporate troublesome components (Cl, F, S, P, and Cr). The study focused on glasses with 20 wt% Na_2O; the range of Na_2O was expanded to 15-35 wt%. A comprehensive study of the solubilities of troublesome components was carried out on the Na_2O-Al_2O_3-CaO-B_2O_3-SiO_2 glass system.

2.0 Experimental Considerations

2.1 Waste Simulants

Waste simulants used in this study included NLLW, DSSF, M-DSSF, and M-RI, as shown in Table 1.1. For purposes of this composition study, these waste simulants were added as solid reagent-grade chemicals. To assess the effect on glass properties from actual slurry wastes, a few glasses were made from both reagent-grade solid chemicals and from simulated slurry wastes. Lokken (1995) described the detailed procedures for makeup of these slurry simulants.

2.2 Glass Melting

The glasses were batched and melted according to PNL Procedure PSL-417-GBM ("Procedure for Glass Batching and Melting, Rev. 0"). For each glass, the major glass components to be varied were batched separately as oxides and carbonates. The remaining components were batched together in constant proportions and treated as a single component, "Others." Others components of the wastes are shown in Table 1.1. Using an Angstrom grinding machine, each batch was then mixed in a grinding cell for 5 min to achieve homogeneous mixture.

About 500 g of each glass was melted in a platinum crucible under a lid (to reduce volatilization) using an electrically heated resistance furnace (Deltech DT-31). Furnace temperature was controlled by a Honeywell controller/programmer and monitored by one S-type thermocouple on the controller and a second independent S-type thermocouple. These thermocouples were located in the middle of the furnace hot zone. Variation in temperature readout from the two thermocouples was $\pm$ 1.0°C with respect to the preset melting temperatures. For better homogeneity, the glass was removed from the furnace after one hour of melting, cooled, crushed in a tungsten-carbide disc mill into a fine powder, and remelted under a lid for another hour. A portion of the molten glass was poured into a bar and annealed for 2 h at 520°C for glass solid characterization and archive purposes. The remaining glass was poured onto a steel plate and air-quenched.
Samples (4-5 g) of selected glasses were sent for elemental analysis for comparison to the as-batched compositions.

2.3 Viscosity Measurements

Viscosity was measured by a rotating-spindle technique and evaluated using standard viscosity-measurement procedures GDL-VSC ("Viscosity Spindle Calibration, Rev. 0") and GDL-VIS ("Standard Viscosity Measurement, Rev. 0"). Each glass sample was heated to its approximate melting temperature (5 Pa.S) in a platinum crucible and was maintained until thermal equilibrium was reached (approximately 30 minutes). A measurement was then taken at the melting temperature and subsequent measurements were taken about 50°C apart. To cover the range of viscosities in the operation of a melter (4 to 10 Pa.S), viscosity measurements were taken first at two decreasing temperatures (viscosity > 5 Pa.S) and then at two increasing temperatures (below 4 Pa.S). To check that viscosity was independent of time, two replicate viscosity measurements were made at the same nominal temperature as that of the initial measurement during the cycle of increasing and decreasing melt temperatures, i.e., the viscosity was measured three times at a temperature. Usually eleven measurements were made for each glass (i.e., three measurements at initial melting temperature and eight duplicate measurements at four temperatures near the melting temperature). The melt viscosity was expected to be affected by volatilization at higher temperatures and by crystallization at low temperatures. Examination of the viscosity changes at the initial melting temperature provides information about how prone each formulation is to volatilization and crystallization.

Temperatures at viscosity = 10 Pa.S were obtained by fitting the raw viscosity at temperature data for each glass to the Arrhenius equation:

$$\mathrm{Ln}(V) = A + B/T \qquad (1)$$

where

A and B = the Arrhenius equation coefficients,
T = temperature (K), and
V = viscosity in Pa.S.

The equipment is checked by following a calibration procedure using National Institute of Standards and Technology (NIST) lead-silicate glass (NBS-711). Previous experience has demonstrated that viscosity measurements of the same glass by different laboratories typically have

good agreement. Also, overcheck measurements of viscosity were made by Corning, Inc. on glass samples provided by this laboratory.

2.4 Durability Testing

The chemical durability of the glasses was determined by two types of tests: PCT and single-pass flow-through. The rationale for using these tests is discussed in Section 1.3.2.

2.4.1 Product Consistency Test (PCT)

The PCT test is based on previous research (Jantzen 1992) and was adapted as PNL Procedure MCC-TP-19 ("Leaching Test Using PCT Test Method, Rev. 0"). The test was conducted using deionized water in Teflon containers at 90°C. New containers were baked at 200°C for one week to drive off fluorine and were then washed thoroughly according to the PCT procedure. The glass was ground in a tungsten-carbide grinding chamber and then sieved through 100- and 200-mesh stainless-steel sieves to obtain particle sizes between 75 and 150 μm. The large particles remaining on the top of the 100-mesh sieve were crushed repeatedly until all glass particles could pass through it. Using an ultrasonic cleaner, the crushed glass was cleaned in deionized water and ethanol. It was then dried, weighed, and 4 g of glass was added to a 60 mL Teflon container filled with 40 mL of deionized water. The ratio of the surface area of glass to solution volume was taken as 2000/m. The Teflon container and its contents were placed for seven days in an oven that had been preheated to 90°C. After the test was terminated, aliquots of the leachate were filtered through a 0.45-μm filter and submitted for chemical elemental analysis. The PCT is performed in duplicate.

Results are reported as normalized elemental-mass releases according to:

$$NL_i = \frac{C_i}{f_i \cdot \frac{S}{V}} \qquad (2)$$

where

NL_i = the normalized mass release based on element i (g/m^2),

C_i = the analyzed concentration of element i in leachate (g/m^3),

f_i = mass fraction of element i in the glass (unitless), and

S/V = the ratio of glass surface are to solution volume (1/m), which is 2000/m here.

Nominal compositions were used for most of the normalized mass release calculations except where the analyzed glass compositions were very different from the nominal compositions.

2.4.2 Single-Pass Flow-Through Test

In this test, monolithic or powdered samples were exposed to controlled environmental conditions, including pH and temperature. A general schematic of the single-pass flow-through test equipment is shown in Figure 2.1. The test equipment uses 13 holding reservoirs for evaluating the effect of pH on dissolution kinetics of various waste form compositions. Twelve of the 13 holding reservoirs are 2000-ml vessels into which a range of pH buffer solutions can be placed, allowing the evaluation of the effect of pH on a single waste-form composition. The single large holding reservoir (25-liter carboy) holds a constant pH solution that is supplied to twelve independent cells/lines from which the dissolution kinetics of 12 varying waste form compositions can be evaluated at a constant pH. The system also can be set up to evaluate 24 varying compositions as a function of a constant pH (i.e., a single buffer solution placed in the twelve 2000-ml vessels as well as the 25-liter carboy). Nitrogen is used continuously as a cover gas for the buffer-solution reservoirs.

Once the test conditions (buffers, flow rates, temperature, etc.) were defined and verified through pretest procedures, a predetermined quantity of glass (powder or monolith) was added to the solution in each preheated, 2-port sample vessel. The 2-port vessels were then sealed and flow of the buffer solution was initiated by activating the pump(s) and the cover gas source. The buffer composition was chosen to minimize compositional overlap between the buffer solution and the glass component. Nitrogen flowed into the 3-port vessels and aided in the transfer of buffer solution to and through the 2-port sample vessels into the sample collection vessels. Flow rates varied depending on the durability of the sample, pH of the buffer solution, and the test temperature. The test conditions were controlled to keep the leachant under saturated with respect to precipitation of secondary phases but above elemental detection limits of the analytical equipment used.

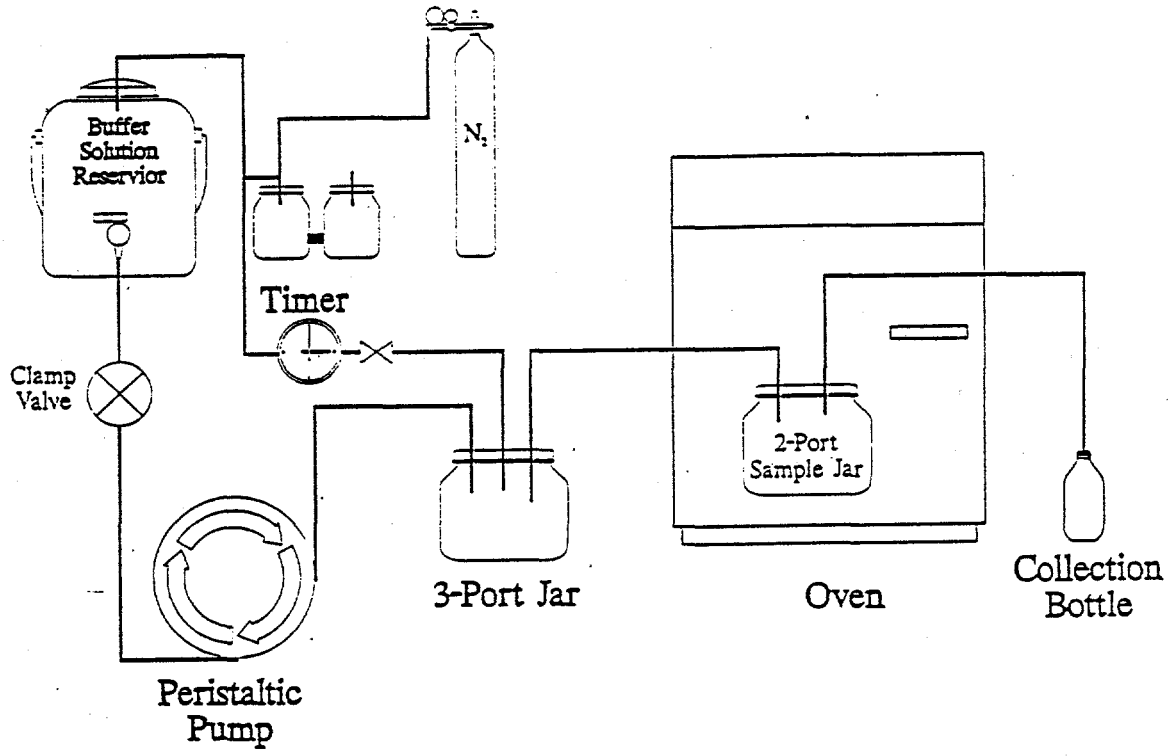


Figure 2.1 Schematic of Single-Pass Flow-Through Apparatus

Corrosion rates in the single-pass flow-through experiments were calculated for each pH value from the steady-state concentrations of component (i) measured in the effluent. The measured concentrations were converted to corrosion rate by:

$$R_{i,j} = \frac{Q_i C_{i,j}}{S_j f_i} \qquad (3)$$

where

$R_{i,j}$ = corrosion rate for component i at time period j ($g/m^2/d$),
$C_{i,j}$ = blank corrected steady-state concentration of Si (g/m^3),
Q_i = flow rate at time period j (m^3/d),
f_i = mass fraction of component i in the sample, and
S_j = average total glass surface area over time period j-1 to j (m^2).

The test conditions for the LLW glasses were as follows:

- Test temperature: 90°C
- Sample size: approximately 1 gram
- Sample type: powder between 75 and 150 μm
- Flow Rate: approximately 100 ml/day
- Buffer solution: 0.0107 m LiOH
  - pH @ 20°C: 11.95 (measured)
  - pH @ 90°C: 10.56 (calculated).

2.4.3 Solution Analyses

Cations and radionuclides were analyzed with inductively coupled plasma atomic emission spectrometry (ICP-AES) with an accuracy of ± 10% for major elements and ± 50% for radionuclides and minor elements. Anions were analyzed with ion chromatography with an accuracy of about 50%. The pH was analyzed with a combination electrode with an accuracy of ± 0.1 pH unit.

3.0 Results and Discussion

3.1 Phase I Vendor Glass Study

Phase I is a "proof of principle" test to demonstrate that a melter system can process a simulated highly alkaline, high nitrate/nitrite content aqueous LLW feed and produce a glass product of consistent quality. Seven melter vendors participated in the Phase I evaluation, including the following: Joule-heated melters from GTS Duratek, Incorporated (GDI); Envitco, Incorporated (EVI); Penberthy Electromelt, Incorporated (PEI); and Vectra Technologies, Incorporated (VTI); a gas-fired cyclone burner from Babcock & Wilcox (BCW); a plasma torch-fired, cupola furnace from Westinghouse Science and Technology Center (WSTC); and a electric arc furnace with top-entering vertical carbon electrodes from U.S. Bureau of Mines (UBM). A detailed technology review on this Phase I study has been reported (Wilson 1995).

3.1.1 Phase I Glass Compositions and Waste

The waste used for the Phase I study is the nominal composition of the double-shell slurry feed (DSSF) as shown in Table 1.1. The nominal glass compositions are shown in Table 3.1 and the full compositions and the selected analyzed compositions are shown in Appendix A1. These glasses include five PNL glasses, LD4-912, LD5-912, LD6-5412, LD6-5510, and LD6-5314. Several vendors one of the PNL glass compositions for their testing. U.S. Bureau of Mines (UBM) used PNL LD6-5510 in its arc furnace with carbon electrodes. Babcock & Wilcox (BCW) used PNL LD6-5510 in its small-boiler simulator-cyclone furnace. The simulator-cyclone furnace uses a slurry composed of the LLW simulant plus glass formers that are injected into a horizontal, gas-fired cyclone burner. Envitco, Incorporated (EVI) used LD4-912 in its ceramic-lined, Joule-heated melter with molybdenum electrodes.

Table 3.1 **Phase I Vendor Glass Compositions and Properties**

	LD4-912	LD5-912	LD6-5412	LD6-5510	LD6-5314	GDI	PEI	WSTC	VTI	EVI	BCW	UBM	EA
Na2O	20.00	20.00	20.00	20.00	20.00	18.82	18.82	18.82	20.00	20.00	20.00	20.00	10.88
K2O	1.46	1.46	1.46	1.46	1.46	3.68	1.44	1.44	1.46	1.46	1.46	1.46	0.04
Al2O3	12.00	12.00	12.00	10.00	14.00	6.14	6.00	18.22	10.00	12.00	10.00	10.00	3.6
B2O3	9.00		5.00	5.00	5.00	6.15		9.45	8.00	9.00	5.00	5.00	11.16
CaO		9.00	4.00	5.00	3.00	7.80	9.77	4.65	2.90		5.00	5.00	1.23
Fe2O3						7.50	1.00		1.00				9.2
Li2O								0.83					4.21
TiO2						1.00							0.65
ZrO2						5.09	2.00	2.10					0.48
SiO2	55.91	55.91	55.91	56.91	54.91	42.23	59.22	42.90	52.90	55.91	56.91	56.91	48.76
MgO									2.10				
Other	1.63	1.63	1.63	1.63	1.63	1.59	1.75	1.59	1.64	1.63	1.63	1.63	1.79
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100
Glass										LD4-912	LD6-5510	LD6-5510	
PCT B,g/m2	0.35		0.11	0.13	0.10	0.60		0.15	0.46		0.05*	0.10*	8.6
PCT Na,g/m2	0.32	1.23	0.38	0.52	0.26	0.72	1.70	0.25	0.55		0.13*	0.32*	6.68
PCT Si,g/m2	0.13	0.22	0.10	0.12	0.09	0.21	0.26	0.08	0.18		0.05*	0.08*	1.8
PCT pH	10.55	12.03	11.39	11.48	11.05	11.46	12.14	10.82	11.12		10.44*	11.06*	11.93
T(C) at 10 PaS	1325	1371	1323	1296	1379	1096	1327	1216	1224				

* These PCT results were obtained from glasses made from the melters that are significantly different from target compositions.

The other four vendors developed their own glass compositions. GTS Duratek, Inc. (GDI) used a composition similar to most high-level waste borosilicate glasses that melt at 1150°C or below, to be able to melt the glass in their ceramic-lined, Joule-heated melter with Inconel electrodes. Penberthy Electromelt, Inc, (PEI) used a boron-free aluminosilicate-glass composition in their ceramic-lined, Joule-heated melter with molybdenum electrodes. Vectra Technologies, Inc. (VTI) used a composition similar to PNL LD6-5510 (replacing 3 wt% SiO_2 with 3 wt% B_2O_3 and replacing 2.1 wt% CaO with MgO) in its Joule-heated furnace with molybdenum electrodes. Westinghouse Science and Technology Center (WSTC) used a high-alumina borosilicate glass in a plasma-torch-fired, cupola furnace. These vendor developed glass compositions were also shown in Table 3.1 and Appendix A1.

From the limited comparison between the nominal compositions and the analyzed composition of the crucible melts performed in this laboratory, our crucible melts composition were usually similar to nominal compositions, as shown in Appendix A. However, the analyzed compositions from some of the glasses produced by Phase I vendors were very different from those of the target compositions (see Appendix A). Most of the discrepancies were between sodium and boron concentrations which tend to volatilize under some melter operating conditions. For example, the analyzed composition of one vendor test glass had sodium contents of 12 wt%, which was 40% less than the targeted 20 wt%. The products with 40% less sodium will be, of course, more durable and this will have a great impact on the PCT results discussed below.

3.1.2 Phase I Glass Durability and Viscosity

The measured PCT releases for some major components of Phase I glasses are listed in Table 3.1; the completed PCT releases are tabulated in Appendix B. These Phase I glasses were all much more durable than the high-level nuclear waste EA glass (designated "EA" glass in Table 3.1). The Babcock and Wilcox (BCW) and US Bureau of Mines (UBM) glasses should have similar durabilities as the PNL LD6-5510 glasses, since they have the same nominal composition. The deviation from the measured PNL LD6-5512 durability is an indication of the deviation in glass composition. The analyzed BCW and UBM glass compositions had much lower sodium and boron contents due to volatilization during melting, as shown in Appendix A. The relative durabilities of the Phase I glasses are shown in Figure 3.1 as measured by 7-day PCT and in Figure 3.2 as measured by single-pass flow-through tests. It is interesting to see that the durability order measured by PCT is different than that measured by flow-through tests. The PEI glass was

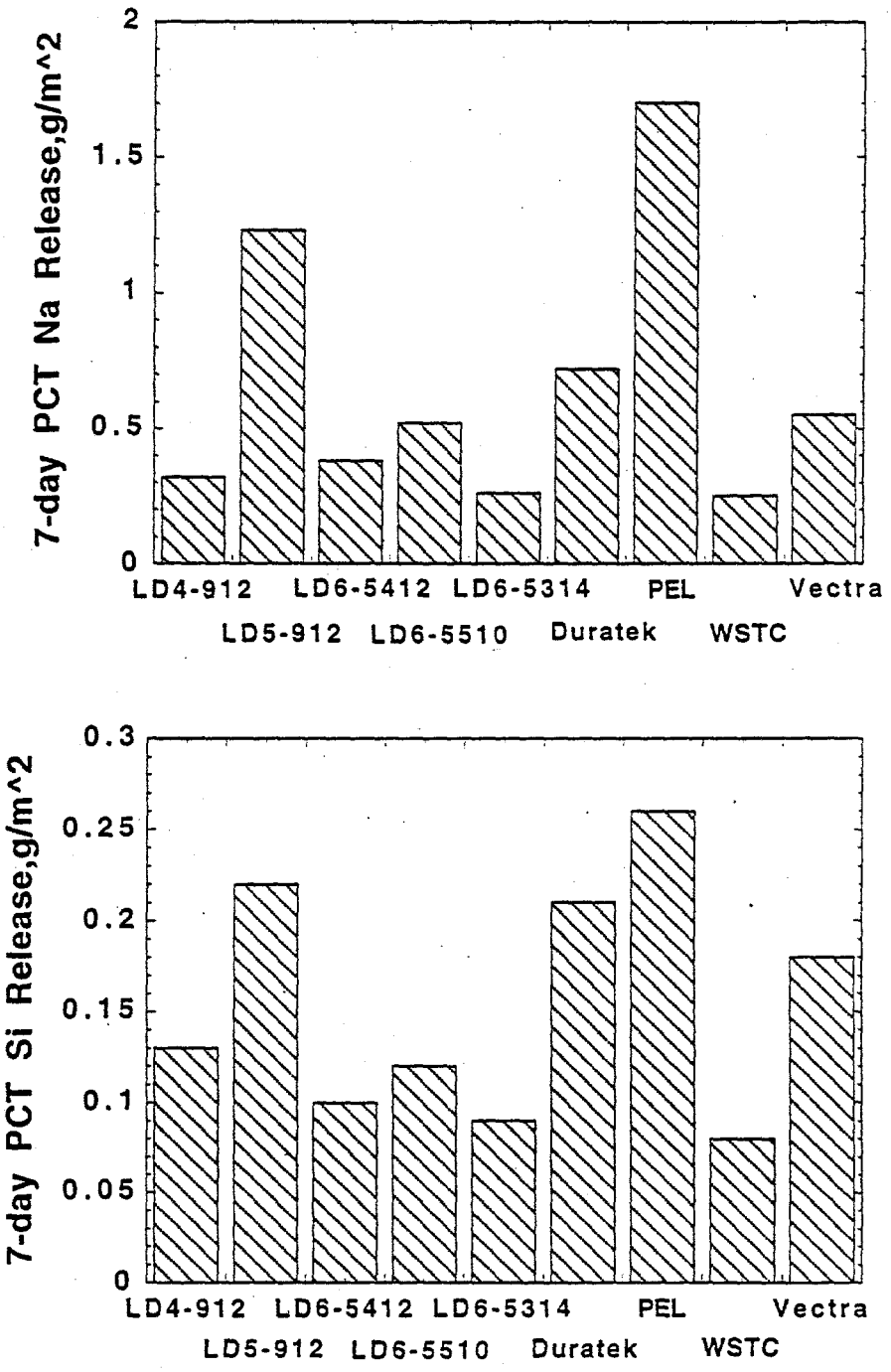


Figure 3.1 7-Day PCT Elemental Releases for Phase I Vendor Glasses Using DSSF Wastes

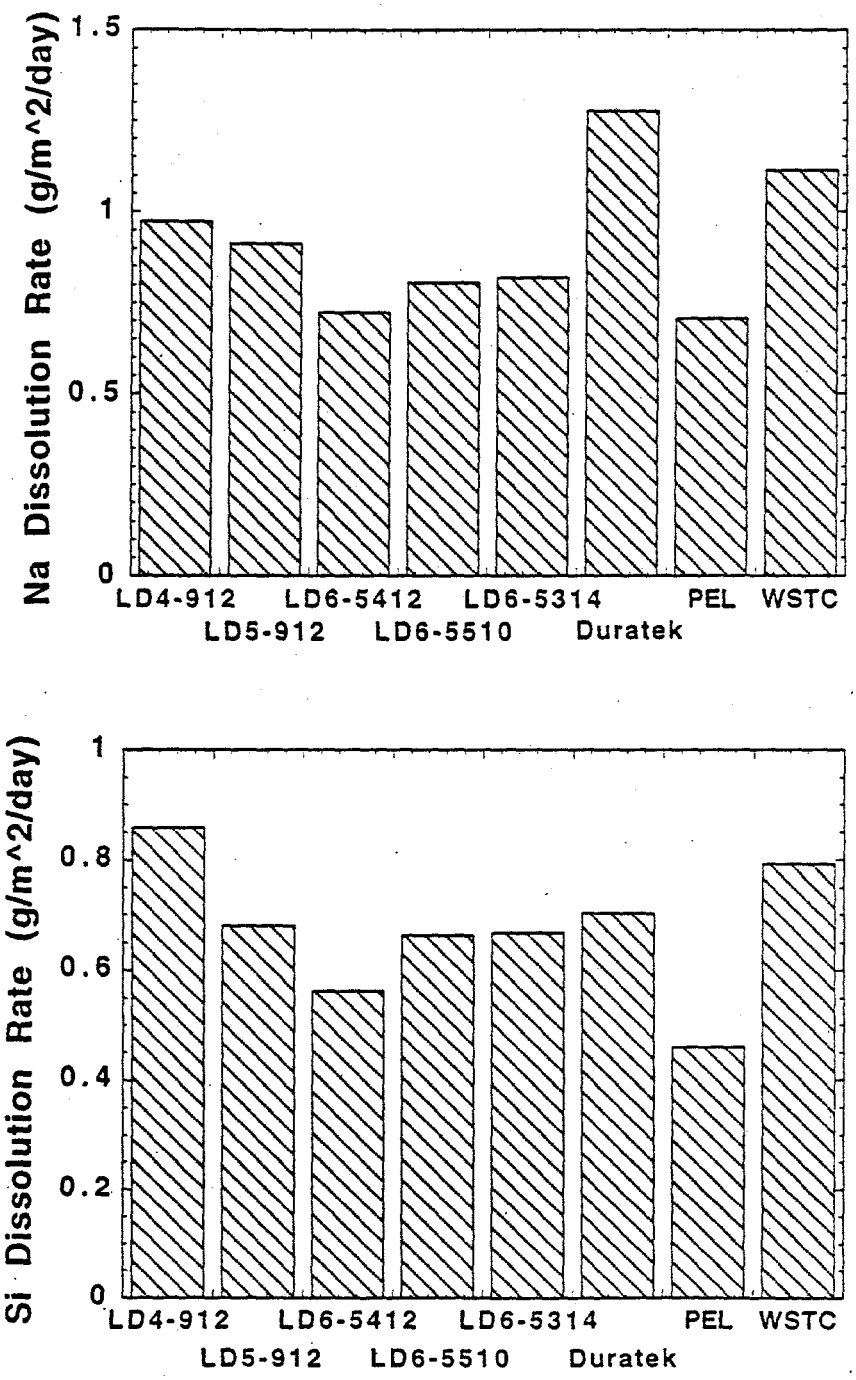


Figure 3.2 Single-Pass Flow-Through Test Elemental Releases for Phase I Vendor Glasses Wastes

the least durable glass as measured by PCT sodium release (Figure 3.1); it was the most durable glass according to flow-through tests (Figure 3.2). This opposite durability order was also observed through testing other LLW glasses with these two types of tests, performed under the current conditions. However, the detailed investigation indicates that PCT results are more sensitive to glass composition change and can be understood according to glass chemistry, while flow-through test results at pH 12 are not useful for glass composition optimization but the results are understandable based on solution chemistry.

The melting temperatures (at 10 Pa.S) of the Phase I glasses are listed in Table 3.1. The temperatures were between 1096° to 1379°C. The GDI composition had the lowest melting temperature; LD6-5314 had the highest melting temperature. The viscosity data from 1000° to 1450°C are tabulated in Table 3.2. The relative melting temperatures of Phase I compositions are also shown in Figure 3.3.

3.2 Phase II Vendor Glass Study

The Phase II glass formulation work supports the overall Phase II vendor testing to allow for more comprehensive testing of equipment and procedures for selected promising technologies. This includes testing the capability of the melter technology to handle wastes with high contents of F, Cl, P, and S. These data will identify melter systems with the greatest flexibility to process feeds with these components and will identify concentration limits for these components that can be realistically processed by vitrification.

Table 3.2. Viscosities of LLW Glasses

		Temp (°C)		Viscosity (Pa*S) at Various Temperatures(°C)											
Vendor	Glass ID	10Pa*S	5Pa*S	A	B	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450
PNL	LD4-912	1325	1424	-9.57	18983	207.7	118.2	70.1	43.1	27.4	18.0	12.1	8.3	5.9	4.2
PNL	LD5-912	1371	1457	-11.69	23002	588.7	297.4	157.9	87.7	50.7	30.3	18.8	12.0	7.8	5.3
PNL	LD6-5314	1379	1474	-10.41	21006	440.7	236.2	132.5	77.4	46.9	29.4	19.0	12.6	8.5	5.9
PNL	LD6-5412	1323	1416	-10.37	20232	249.7	136.9	78.5	46.8	28.9	18.4	12.1	8.1	5.6	3.9
PNL	LD6-5510	1296	1384	-10.78	20525	208.9	113.6	64.6	38.2	23.4	14.8	9.7	6.5	4.4	3.1
PNL	LD6-5510c	1294	1399	-8.78	17371	129.6	77.4	48.0	30.8	20.3	13.8	9.6	6.8	5.0	3.7
PNL	LDM-0912	1348	1439	-10.72	21110	350.9	187.5	104.9	61.1	36.9	23.1	14.9	9.8	6.7	4.6
PNL	LDM-1	1365	1450	-11.80	23101	571.4	287.9	152.4	84.4	48.7	29.1	18.0	11.4	7.5	5.0
PNL	LDM-2	1345	1433	-11.12	21727	381.2	200.0	110.0	63.1	37.6	23.2	14.7	9.6	6.4	4.4
PNL	LDM-3	1376	1464	-11.40	22600	571.3	292.1	156.8	88.0	51.3	31.0	19.4	12.4	8.2	5.5
PNL	LDM-4	1161	1232	-12.43	21133	64.4	34.4	19.2	11.2	6.8	4.2	2.7	1.8	1.2	0.8
PNL	LDM-5412	1310	1410	-9.42	18563	174.1	100.3	60.2	37.4	24.0	15.9	10.8	7.5	5.3	3.9
PNL	LDMS-1	1376	1462	-11.64	22988	611.4	309.0	164.2	91.2	52.7	31.6	19.5	12.5	8.2	5.5
PNL	LDMSM-1	1323	1406	-11.73	22389	350.7	180.5	97.5	55.0	32.2	19.6	12.3	7.9	5.2	3.6
PNL	LRM-0912	1381	1473	-10.88	21810	517.8	271.0	148.7	85.1	50.6	31.1	19.7	12.9	8.6	5.9
PNL	LRM-1	1334	1419	-11.48	22158	372.7	193.1	104.9	59.5	35.1	21.4	13.5	8.7	5.8	4.0
PNL	LRM-2	1380	1471	-10.86	21751	505.7	265.1	145.7	83.5	49.7	30.6	19.5	12.7	8.5	5.8
PNL	LRM-3	1411	1498	-11.83	23804	956.8	472.0	245.2	133.3	75.6	44.5	27.1	17.0	11.0	7.2
PNL	LRM-4	1165	1232	-13.32	22472	75.9	39.0	21.0	11.8	6.9	4.2	2.6	1.7	1.1	0.8
PNL	LRM-5412	1356	1464	-8.82	18113	223.6	130.6	79.3	49.9	32.4	21.6	14.8	10.4	7.5	5.4
PNL	LRMS-1	1338	1425	-11.12	21616	351.3	185.0	102.0	58.7	35.0	21.7	13.8	9.0	6.1	4.2
PNL	LRMSM-1	1297	1379	-11.64	21889	258.4	134.9	73.9	42.2	25.0	15.4	9.7	6.3	4.2	2.9
PNL	SSHTM-1	1333	1410	-12.91	24429	535.0	259.1	132.3	70.8	39.5	22.9	13.8	8.5	5.4	3.6
GDI	Duratek	1096	1163	-12.58	20381	30.8	16.8	9.6	5.7	3.5	2.2	1.5	1.0	0.7	0.5
PEI	PEI	1327	1414	-11.15	21515	315.2	166.4	92.1	53.1	31.8	19.7	12.6	8.2	5.5	3.8
VTI	VECTRA I	1224	1318	-9.49	17657	79.7	47.2	29.0	18.5	12.1	8.2	5.7	4.0	2.9	2.1
WSTC	WSTC	1216	1306	-9.94	18233	80.0	46.5	28.2	17.7	11.4	7.6	5.2	3.6	2.6	1.9

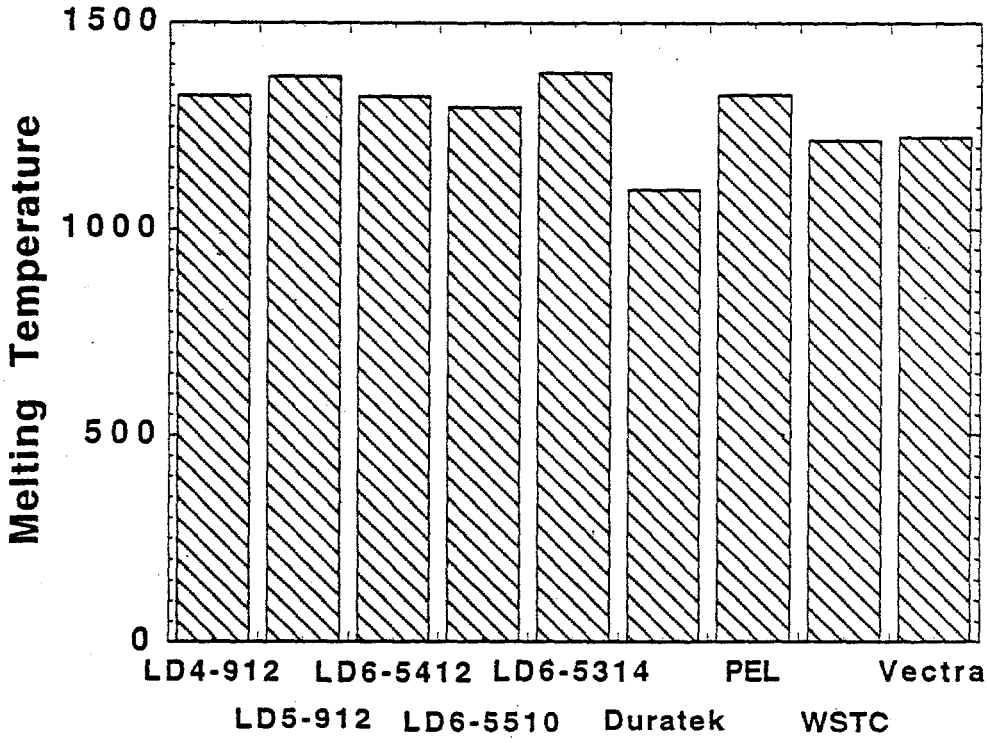


Figure 3.3 Melting temperatures at 10 Pa▪s for phase I vendor glasses using DSSF wastes.

To accommodate the highest contents of F, Cl, P, and S in the Phase II glasses, the Phase II formulations were developed based on the following:

- the available minor component solubility data in LLW glasses as presented in Li, (1995);
- expansion from the Phase I glass compositions;
- waste loading at the equivalent of 20 wt% Na_2O but at higher minor component concentrations in the simulants;
- exploration of the trade-off between melt temperature vs durability (e.g., 100 poise temperature vs PCT response) to determine how much difference there might be among viscosity and implied volatility with respect to durability;
- examination of the effect of different sources of glasses formers including ZrO_2 and Fe_2O_3 as well as SiO_2 and B_2O_3;
- search for a good-quality glass, i.e., a glass with good long-term durability and reasonable viscosity; and
- providing much wider melting temperature ranges, from approximately 1100° to 1450°C, to give the vendors more flexibility.

3.2.1 Phase II Glass Composition and Wastes

The simulated wastes used for the Phase II study are the modified DSSF (M-DSSF) and the modified remaining inventory (M-RI), as shown in Table 1.1. The M-DSSF simulant had 3 wt% F and 2.4 wt% Cl, which represented the highest possible fluorine and chlorine contents in the LLW waste streams. The M-RI simulant contained 9.95 wt% of P_2O_5 and 3.98 wt% SO_3, which represented the highest possible phosphorus and sulphur contents in the LLW streams. The 25 wt% waste-loading requirement translated to 0.75 wt% F and 0.6 wt% Cl in the glass formulations with M-DSSF, which are similar to the solubility limits of F and Cl in LLW glasses shown in Table 3.3 . A 25 wt% loading of M-RI meant 2.48 wt% P_2O_5 and 0.995 wt% of SO_3 in glass formulations with M-RI, which exceeded some solubility limits in some glasses, especially for SO_3 as shown in

Table 3.3 and Table 3.4. Based on these considerations for the solubility of minor components S, P, Cl, and F, 12 glass formulations were tested as Phase II compositions shown in Tables 3.5 and 3.6.

These 12 glasses are divided into two groups: six LDM-glasses, made from M-DSSF simulant and six LRM-glasses, made from M-RI simulant.

- LRM-5412 was based on LD6-5412; the only difference between these two glasses is the difference in waste composition. LRM-5412 used the M-RI simulant and had high contents of P_2O_5 and SO_3. This glass was expected to be able to accommodate 25 wt% of M-RI without phase segregation and phase separation according to the results presented in Section 3.2.

- LRM-1 was modified from LRM-5412 by replacing 3 wt% B_2O_3, 2 wt% CaO, and 6 wt% SiO_2 with 6 wt% Fe_2O_3, 4 wt% ZrO_2, and 1 wt% Li_2O. LRM-1 was predicted to have had better chemical durability, especially in terms of the long-term durability due to the reduction of CaO and addition of ZrO_2 and lower melting temperature.

- LRM-0912 was based on LD5-0912 which was shown to be able to accommodate high levels of P_2O_5 and SO_3.

- LRM-2 was improved from LRM-0912 by replacing 3 wt% CaO and 3 wt% SiO_2 with 6 wt% Fe_2O_3. The durability, especially the long-term durability, was predicted to be improved and the melting viscosity should have been similar.

- LRM-3 was predicted to be a glass with good chemical durability, especially in terms of long-term durability, by eliminating CaO and keeping the correct amounts of ZrO_2, B_2O_3, and Al_2O_3.

- LRM-4 was predicted to be a glass with good short-and long-term chemical durability, but could be melted at a temperature below 1200°C.

The LDR-1, LDM-2, LDM-3, LDM-4, LDM-0912, and LDM-5412 glasses were formulated for the same purposes as were the corresponding LRM-glasses discussed above.

Table 3.3

Measured Solubility Limits (wt%) of Minor Components in LLW Glasses as a Function of Glass Processing Temperature

Glass	L6-5412			L4-9012
Minor Component	1300 C	1350 C	1400 C	1350 C
Cl (#)	0.56 (0.03)	0.57 (0.03)	0.52 (0.03)	0.49 (0.04)
F (#)	0.77 (0.02)	0.92 (0.02)	0.91 (0.02)	1.18 - 1.45
P2O5 (#)	1.94 (0.16)	2.10 (0.16)	2.28 (0.17)	5.8 (*)
SO3 (#)	0.75 (0.06)	0.75 (0.07)	0.75 (0.07)	0.47 (0.04)
Cr2O3 (&)	0.46	0.48 (0.02)	0.48 (0.02)	1.04 (0.07)

(#) Values in aparenthese are one standard deviation, except for Cr2O3 case.
(&) For Cr2O3, values in apparenthese are differences between Na- and K- fussion methods used in ICP.

Table 3.4

Measured Concentrations (wt%) of P_2O_5 and SO_3 in LLW Glasses and Visual Inspection of Phase Separation

Glass	L6-5412	L4-9012	L4-909	L5-0912
P2O5 (#)	2.24 (0.21)	2.20 (0.19)	2.05 (0.18)	2.29 (0.23)
SO3 (#)	0.88 (0.07)	0.57 (0.05)	0.68 (0.06)	1.00 (0.08)
Phase Separation	slightly	significant	intermediate	non

(#) Values in aparenthese are one standard deviation.

Table 3.5 Phase II Vendor Glass Nominal (Top) and Analyzed (Bottom) Compositions For M-DSSF

OtherD Oxide	M-DSSF waste (wi)
Cr2O3	0.15
Cs2O	0.53
Fe2O3	0.01
K2O	5.31
MgO	0.01
MnO2	0.01
MoO3	0.54
SrO	0.38
P2O5	0.69
SO3	0.79
Cl	2.38
F	3.02
I	0.47
Total	14.29

Glass oxide	waste (wi)	LDM-1 (gi)	LDM-2 (gi)	LDM-5412 (gi)	LDM-0912 (gi)	LDM-3 (gi)	LDM-4 (gi)
SiO2	0.00	50.14	52.14	55.14	55.14	52.14	44.14
B2O3	0.00	2.00	0.00	5.00	0.00	6.00	6.00
Na2O	74.02	20.00	20.00	20.00	20.00	20.00	20.00
CaO	0.01	2.00	6.00	4.00	9.00	0.00	6.00
Al2O3	11.69	12.00	12.00	12.00	12.00	12.00	10.00
ZrO2	0.00	4.00	0.00	0.00	0.00	6.00	4.00
Fe2O3	0.00	6.00	6.00	0.00	0.00	0.00	6.00
Li2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OtherD	14.29	3.86	3.86	3.86	3.86	3.86	3.86
Total	100.01	100.00	100.00	100.00	100.00	100.00	100.00

Glass oxide	waste (wi)	LDM-1 (gi)	LDM-2 (gi)	LDM-5412 (gi)	LDM-0912 (gi)	LDM-3 (gi)	LDM-4 (gi)
SiO2		50.06	51.87	53.56	55.30	53.50	43.70
B2O3		2.01		5.01		6.31	6.25
Na2O		21.05	20.30	21.22	19.92	18.85	20.36
CaO		1.78	6.24	3.94	9.60	0.12	6.48
Al2O3		12.17	12.08	12.05	12.22	12.44	10.06
ZrO2		4.02	0.01			5.27	3.82
Fe2O3		6.21	6.19	0.06	0.06	0.05	6.14
Li2O							
OtherD		2.70	3.31	4.18	2.89	3.45	3.18
Total		100.00	100.00	100.00	100.00	100.00	100.00

Table 3.6 Phase II Vendor Glass Nominal (Top) and Analyzed (Bottom) Compositions For M-RI

OtherR Oxide	M-RI waste (wi)
Cr2O3	0.14
Cs2O	0.60
Fe2O3	0.01
K2O	0.12
MgO	0.00
MnO2	0.04
MoO3	0.61
SrO	0.44
P2O5	9.95
SO3	3.98
Cl	0.14
F	1.04
I	0.54
Total	17.61

Glass oxide	waste (wi)	LRM-1 (gi)	LRM-2 (gi)	LRM-5412 (gi)	LRM-0912 (gi)	LRM-3 (gi)	LRM-4 (gi)
SiO2	0.00	48.54	51.54	54.54	54.54	51.54	43.04
B2O3	0.00	2.00	0.00	5.00	0.00	6.00	6.00
Na2O	78.93	20.00	20.00	20.00	20.00	20.00	20.00
CaO	0.01	2.00	6.00	4.00	9.00	0.00	6.00
Al2O3	3.46	12.00	12.00	12.00	12.00	12.00	10.00
ZrO2	0.00	4.00	0.00	0.00	0.00	6.00	4.00
Fe2O3	0.00	6.00	6.00	0.00	0.00	0.00	6.00
Li2O	0.00	1.00	0.00	0.00	0.00	0.00	0.50
OtherR	17.61	4.46	4.46	4.46	4.46	4.46	4.46
Total	100.01	100.00	100.00	100.00	100.00	100.00	100.00

Glass oxide	waste (wi)	LRM-1 (gi)	LRM-2 (gi)	LRM-5412 (gi)	LRM-0912 (gi)	LRM-3 (gi)	LRM-4 (gi)
SiO2		47.42	48.20	53.41	53.19	54.21	41.74
B2O3		2.02		5.09	0.03	6.25	6.01
Na2O		21.23	22.13	20.27	20.42	17.75	20.22
CaO		1.82	6.13	4.23	9.41	0.19	6.19
Al2O3		12.19	11.41	11.86	11.79	12.37	9.77
ZrO2		3.99				4.97	3.82
Fe2O3		6.24	5.87	0.05	0.05	0.05	5.98
Li2O		1.02					0.49
OtherR		4.05	6.25	5.09	5.11	4.20	5.78
Total		100.00	100.00	100.00	100.00	100.00	100.00

3.2.2 Phase II Glass Melting from Dry Chemicals

LRM-5412 was melted at 1350°C; its 10 Pa.S temperature was 1356°C. The glass was green in color and homogeneous and no phase segregation was observed during melting.

LRM-1 was melted at 1345°C; the glass was black-brown in color. During the first hour of melting, a yellow layer was observed on top of the glass and some yellow material (probably Na_2SO_4) was found at the top interface between the cooled glass and the Pt crucible and also on part of the center surface, as shown in Figure 3.4, after the second one-hour melting at 1345°C. The measured temperatures at 10 Pa.S was 1334°C, as shown in Table 3.2.

LRM-0912 was melted at 1375°C; its 10 Pa.S temperature was 1381°C. A layer of white materials was observed on top of the melt after 30 minutes melting (Figure 3.5a); the white layer disappeared after one hour of melting (Figure 3.5b). Bubbles formed in the melt during cooling, as shown in Figure 3.5b. The glass was reground and melted for the second hour at 1375°C. The glass was dark green in color, free of white layers, but had some small bubbles.

LRM-2 was melted at 1360°C and a yellow layer was observed on top of the melt during the first 30 minutes. Bubble formation was observed after the crucible was removed from the furnace after the first one-hour melting, as shown in Figure 3.6. The second melting at the same temperature still produced bubbles after one hour of melting, as shown in Figure 3.6d. A small amount of yellow materials similar to those observed in LRM-0912 around the glass at the interface with the Pt crucible was observed. The glass was dark-brown in color. The measured 10 Pa.S temperatures was 1380°C. The observed bubble formation was due in part to the higher viscosity resulting from the low melting temperature relative to the measured 10 Pa.S temperature (1360° verse 1380°C).

LRM-3 was melted at 1440°C and no phase segregation was observed during either the first or second melting as shown in Figure 3.7. However, the glass was cloudy and yellow-green in color. The cloudiness suggested phase separation during cooling; the crystallinity is being investigated. The measured 10 Pa.S temperature was 1411°C.

LRM-4 was melted at 1140°C and a light brown layer was observed on top of the melt after 30 minutes melting during the first melting, as shown in Figure 3.8. The light-brown surface layer gradually dissolved in the melt as the melting duration increased, as shown in Figure 3.8.

a

LRM-1 1st melt / 1hr.
Yellow impressed surface of glass.

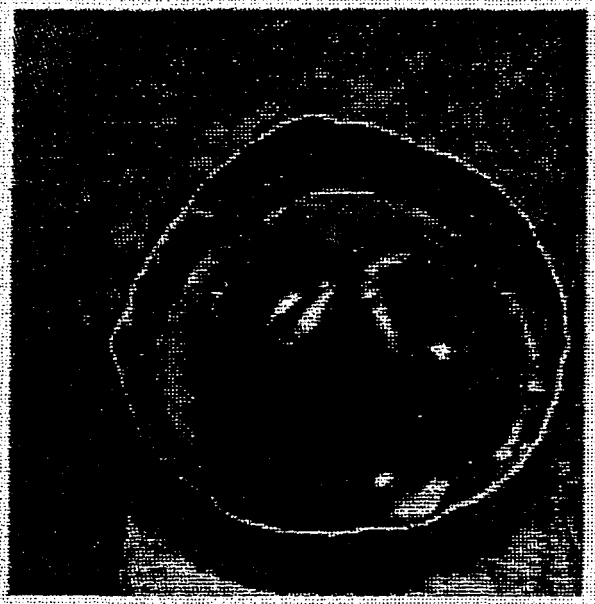
b

LRM-1 2nd melt 1hr
Yellow round edge of glass.

Figure 3.4 LRM-1 was melted for (a) the 1st hour at 1345 C and (b) for the second hour at 1345 C.

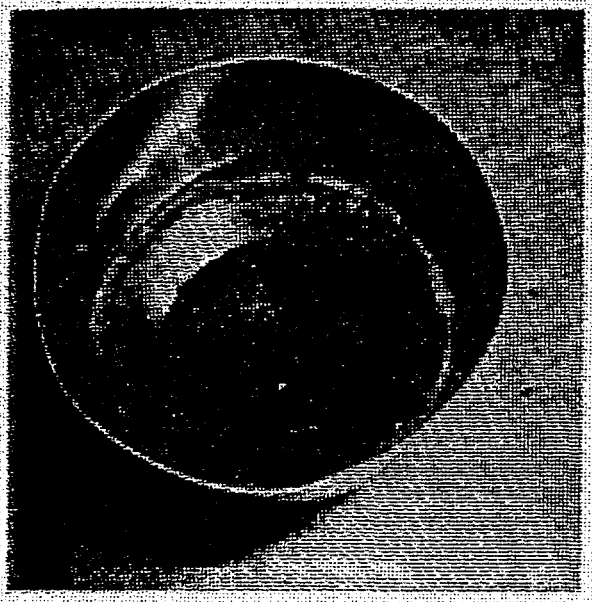
a

LRM-0912 1st melt 30 min.
Glass looked light green. Green around edges.



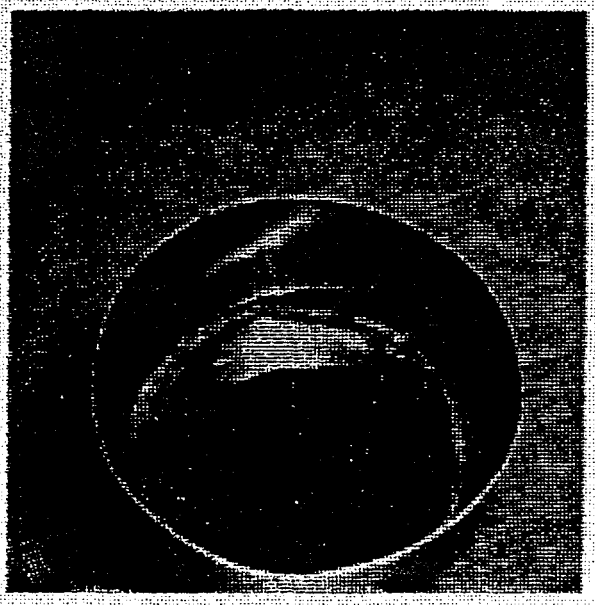
b

LRM-0912 1st melt 1hr.
Bubbles formed after quenching light green glass around edge.



c

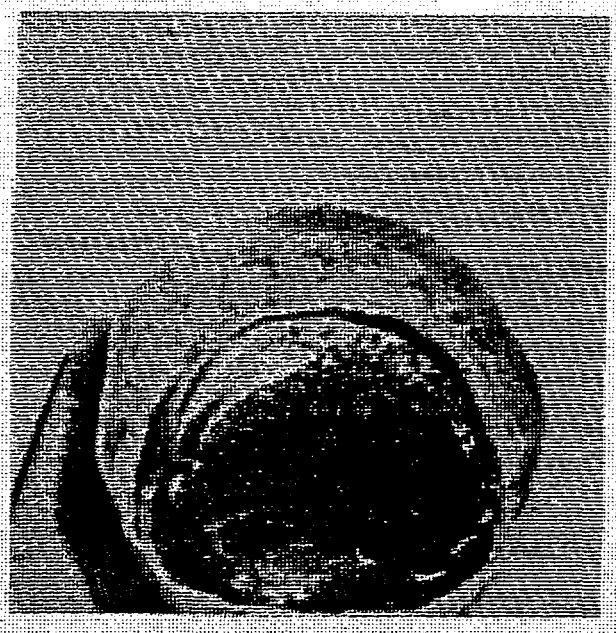
LRM-0912 2nd melt 1hr.
Protection 15 min later.
Glass is reddish brown color.
Glass dark green.



d

LRM-0912 2nd melt 1hr
Glass a dark green in color.

Figure 3.5 LRM-0912 was melted at 1375 C:
(a) for 30 min. during the first melting
(b) for 60 min. during the first melting
(c) for 60 min. during the second melting, 15 min after cooling
(d) for 60 min, during the second melting, immediately out of oven.

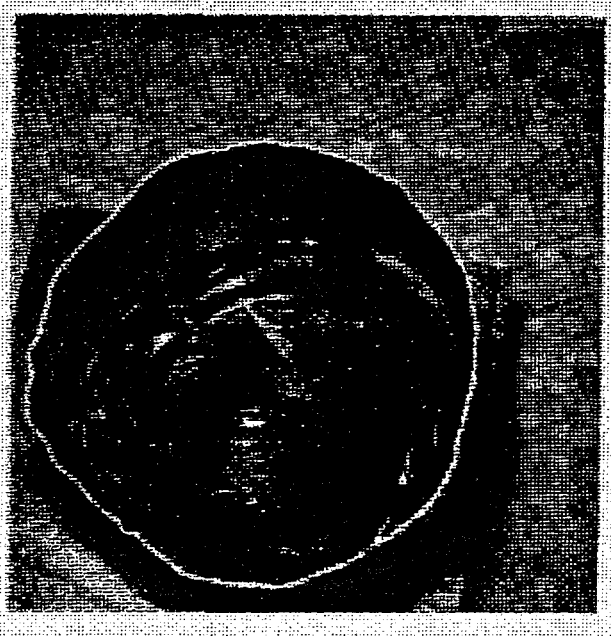


a

LRM-2 1st melt 30 min
Yellow above surface of glass

b

LRM-2 1st melt 1 hr
Yellow around surface of glass w/ large bubbles after heating.



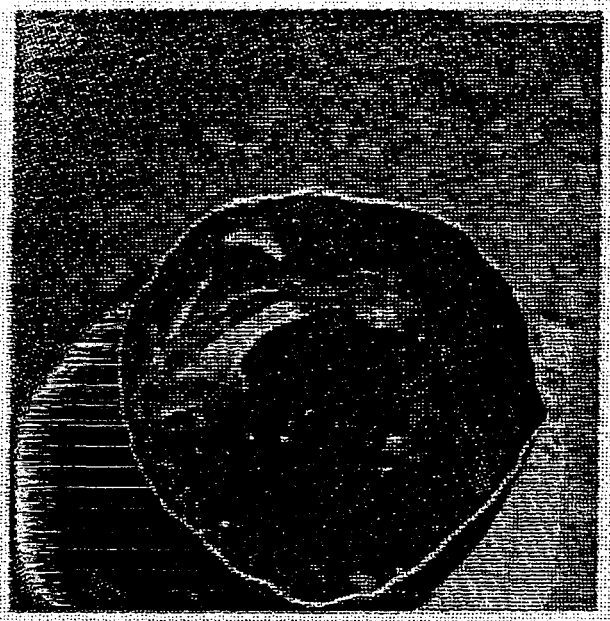
c

LRM-2 1st melt 30 min
Taken 5 min later.
Yellow above surface.

d

LRM-2 2nd melt 1hr
Bubbles formed after quenching.
Yellow around surface.

Figure 3.6 LRM-2 was melted at 1360 C;
(a) for 30 min. during the first melting
(b) for 60 min. during the first melting
(c) for 30 min. during the second melting
(d) for 60 min. during the second melting.



a

LRM-3 1st melt 30 min
Photo taken 5 min after.
Glass is cloudy green.

b

LRM-3 1st melt 1 hr.
Glass is Opened, glass is a
cloudy yellow green.

c

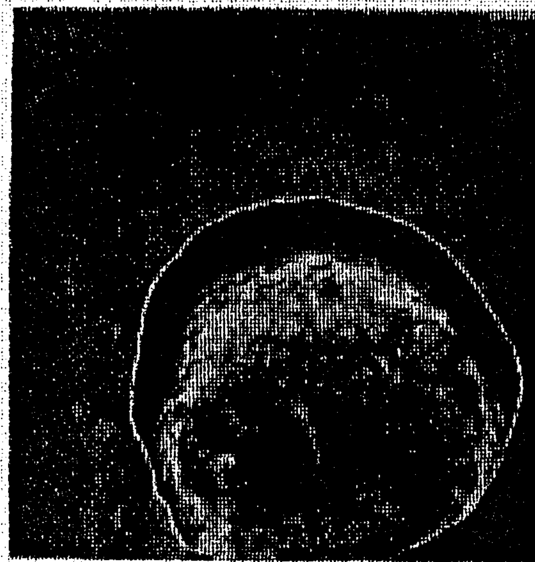
LRM-3 2nd melt 30 min
Glass is a cloudy green.

d

LRM-3 2nd melt 1 hr.
Glass is a cloudy dark green
color.

Figure 3.7 LRM-3 was melted at 1644 C.
(a) for 30 min. during the first melting
(b) for 60 min. during the first melting
(c) for 30 min. during the second melting
(d) for 60 min. during the second melting.

a



LRM-4 1st melt 30min
Light brown layer on glass surface and walls of crucible during this melt.

b

LRM-4 1st melt 1hr
Brown layer around walls of crucible. Large bubble in middle after quenched

c

LRM-4 2nd melt 1hr
Yellow around edge of glass.

Figure 3.8 LRM-4 was melted at 1140 C:
(a) for 30 min. during the first melting
(b) for 60 min. during the first melting
(c) for 60 min. during the second melting

This disappearance of the light-brown surface layer was not due to volatilization, as indicated by the high retention of SO_3 and P_2O_5 contents in the glass analysis results.

All six of the LDM-glass series melted smoothly without obvious phase segregation and separation. The melting temperature for LDM-5412 was 1290°C and the glass was light-green in color. The measured 10 Pa.S temperature was 1310°C. The melting temperature for LDM-1 was 1310°C and the glass was black-yellow in color. The measured 10 Pa.S temperature was 1365°C. The melting temperature for LDM-0912 was 1381°C and the glass was yellow-green in color. The measured 10 Pa.S temperature was 1348°C. The melting temperature for LDM-2 was 1320°C and the glass was yellow-black in color. The measured 10 Pa.S temperature was 1345°C. The melting temperature for LDM-3 was 1410°C and the glass was green in color. The measured 10 Pa.S temperature was 1376°C. The melting temperature for LDM-4 was 1130°C and the glass was black in color. The measured 10 Pa.S temperature was 1161°C.

The detailed measurements of viscosities for Phase II glasses are shown in Figures 3.9 and 3.10. The comparison of the melting temperature, at 10 Pa.S, among the Phase II glasses are shown in Figure 3.11. This figure demonstrates that the LDM-glasses usually had lower melting temperatures due to the F content in the M-DSSF simulant than did the corresponding LMR-glasses, due to the P and S contents in the M-RI simulant. LD5-0912 had a melting temperature (at 10 Pa.S) of 1371°C, as shown in Table 3.2. The melting temperatures for LDM-0912 and LRM-0912 were 1348° and 1381°C, respectively. The addition of 0.8 wt% F and 0.6 wt% Cl reduced the melting temperature by over 20°C, while the addition of 2.5 wt% P_2O_5 and 1.0 wt% SO_3 increased the melting temperature by 10°C. LD6-5412 had a melting temperature (at 10 Pa.S) of 1323°C, as shown in Table 3.2. The melting temperatures for LDM-5412 and LRM-5412 are 1310° and 1356°C, respectively. The addition of 0.8 wt% F and 0.6 wt% Cl reduced the melting temperature by 13°C while addition of 2.5 wt% P_2O5 and 1.0 wt% SO_3 increased the melting temperature by 33°C.

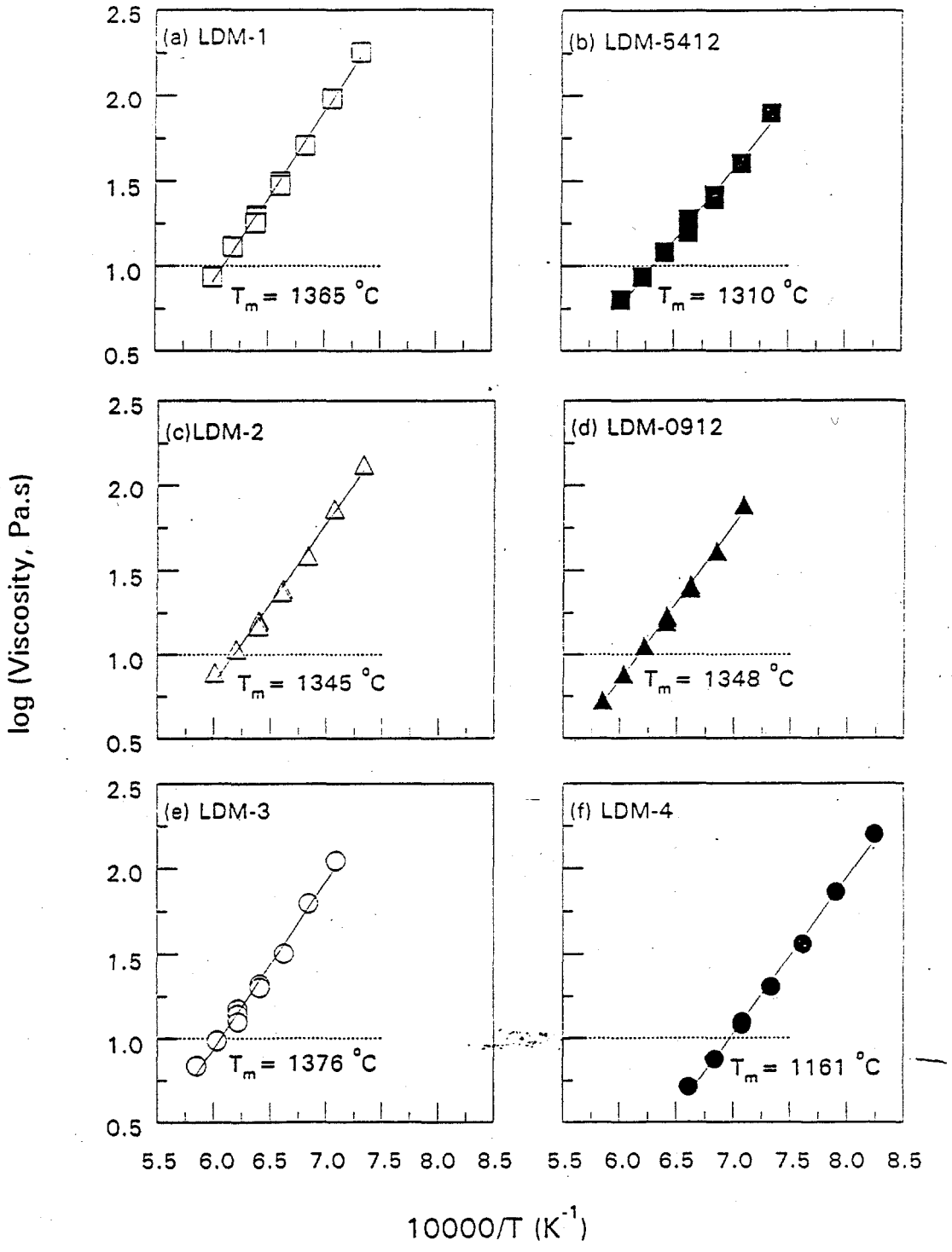


Figure 3.9 Viscosity measurements and 10 Pa•s temperature (Tm) for (a) LDM-1, (b) LDM-5412, (c) LDM-2, (d) LDM-0912, (e) LDM-3 and (f) LDM-4.

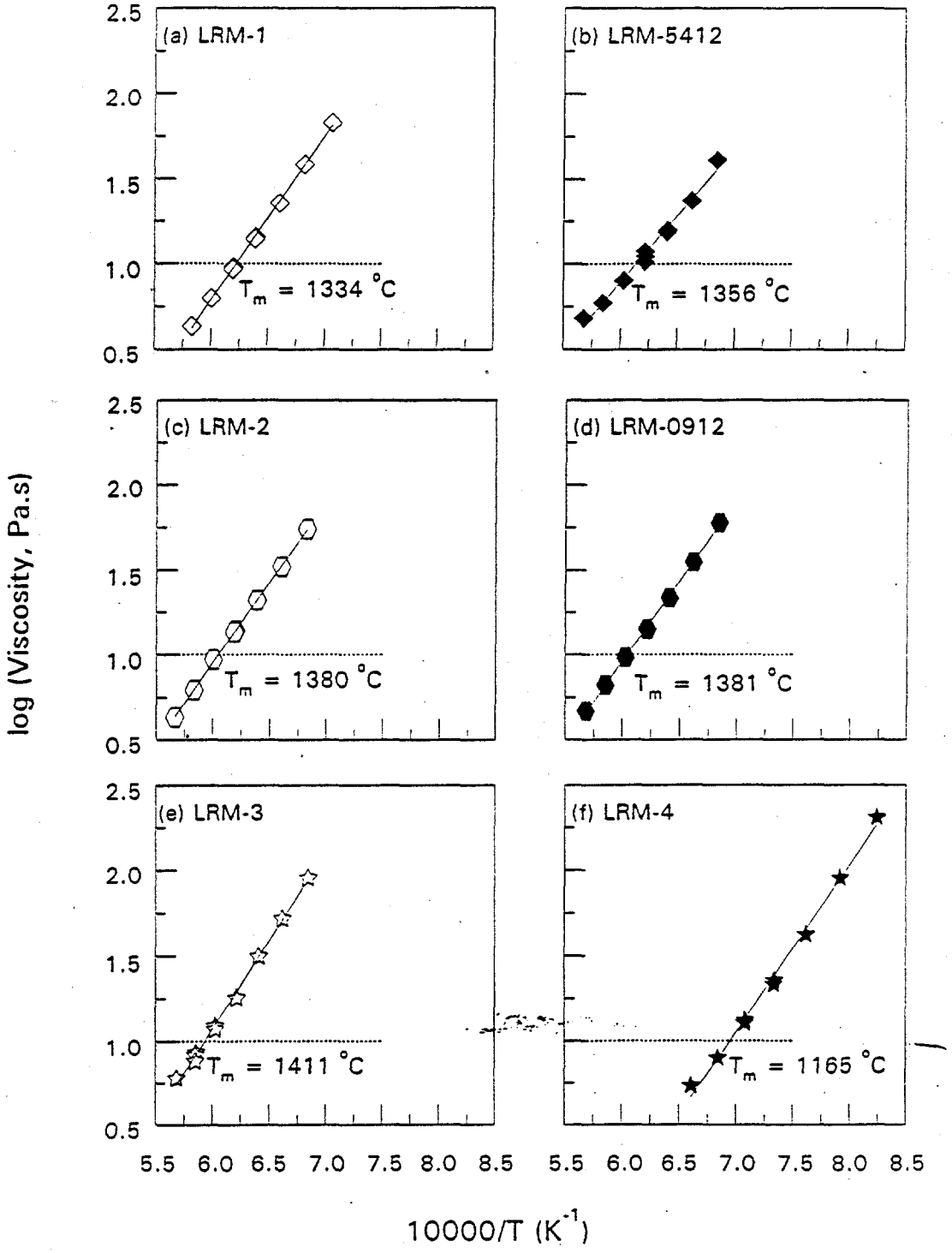


Figure 3.10 Viscosity measurements and 10 Pa•s temperature (Tm) for (a) LRM-1, (b) LRM-5412, (c) LRM-2, (d) LRM-0912, (e) LRM-3 and (f) LRM-4.

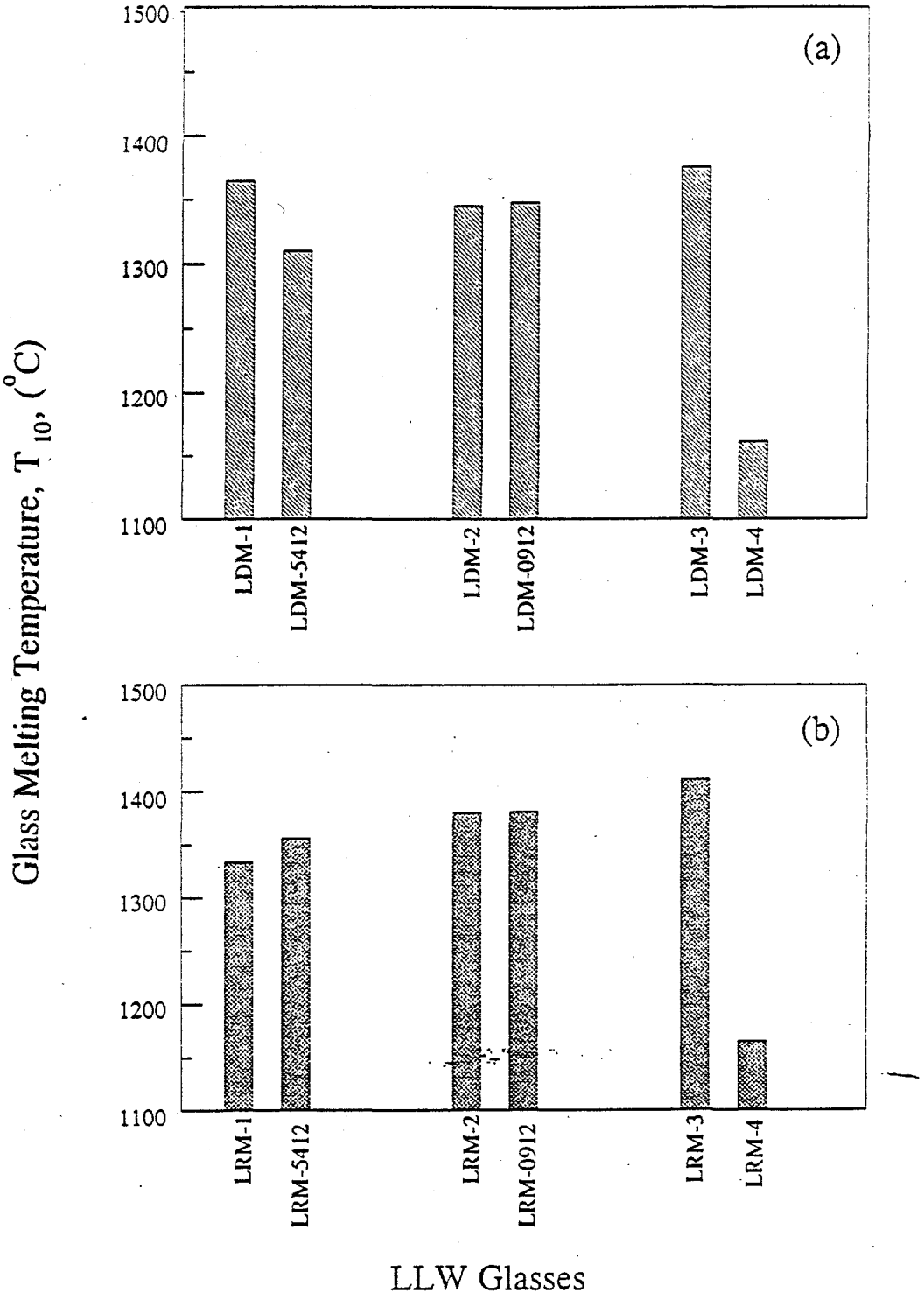


Figure 3.11 Comparison of melting temperature, at 10 Pa•s among (a) LDM glasses and (b) LRM glasses.

3.2.3 Solubilities of F, Cl, S, and P in Phase II Glasses

The nominal concentrations of F and Cl in the LDM-glasses were 0.82 and 0.64 respectively, which were expected to be close to the solubility limits as shown in Table 3.3 and caused no difficulties in crucible melting as discussed above. The actual contents of F and Cl in LDM-glasses have not been analyzed yet.

The analyzed SO_3 and P_2O_5 contents were similar to the nominal composition in the LDM-glasses. The P_2O_5 contents in LRM-glasses were also the same as the nominal composition, as shown in Table 3.7. Among the LRM-glasses, LRM-0912 and LRM-4 composition were able to accommodate almost 100% of the SO_3 and P_2O_5 added to the batching mixture under crucible-melting conditions without significant phase segregation and phase separation. LRM-3 was least capable of retaining SO_3 under the crucible-melting condition because it had the least NBO bonds available in this formulation. LRM-5412, LRM-1, and LRM-2 had slightly lower SO_3 contents than did the targeted values due to volatilization.

Another special property of our crucible melting is the high oxidizing conditions. The chemicals used in the crucible melting are high valance oxides such as Fe_2O_3; the contact of laboratory air with the small volume of melt in the crucible was good and resulted in a strong oxidizing condition. The analysis of the ratio of Fe(II) to total Fe for the Fe-containing phase II glasses are shown in Table 3.8 for LRM-1, LRM-2, LRM-4, LDM-1, LDM-2, and LDM-4, respectively. The majority of irons are still in the Fe(III) state. In general, more Fe(II) were present in LRM glasses than were in LDM-glasses, which may be an indication of the reduction of iron by sulphur in the LRM-glasses. Another obvious trend was that the glasses melted at high temperature were more reduced, as seen from the comparison of the ratios of Fe(II)Fe between low-temperature glass, LRM-4, with LRM-1 and LRM-2, or by comparison between LDM-3 with LDM-1 and LDM-2. One should be aware of that when the melting condition becomes reducing, it may affect the solubilities of minor components, as well as processing difficulties such as foaming and decreasing durabilities. This is especially true for those Fe-containing formulations where iron will be reduced to Fe(II).

Table 3.7. Sulfur and Phosphorus Contents in Phase II Glasses (wt%)

Glass	LRM-5412	LRM-1	LRM-0912	LRM-2	LRM-3	LRM-4
Nominal SO_3	1.01	1.01	1.01	1.01	1.01	1.01
Analyzed SO_3	0.87	0.76	1.01	0.74	0.59	0.93
Nominal P_2O_5	2.52	2.52	2.52	2.52	2.52	2.52
Analyzed P_2O_5	2.67	2.72	2.67	2.60	2.82	2.62
Glass	LDM-5412	LDM-1	LDM-0912	LDM-2	LDM-3	LDM-4
Nominal SO_3	0.21	0.21	0.21	0.21	0.21	0.21
Analyzed SO_3	0.69	0.22	0.26	0.23	0.21	0.26
Nominal P_2O_5	0.19	0.19	0.19	0.19	0.19	0.19
Analyzed P_2O_5	0.62	0.46	0.24	0.28	0.28	0.27

Table 3.8. Redox State of Phase II Glasses Measured by Fe(II)/Fe Ratio

Glass	Wt % Fe(II) in Glass	Wt% Fe (total) in Glass	Ratio of Fe(II)/Fe
LRM-1	0.2669	3.5585	0.075
LRM-2	0.3190	2.9045	0.110
LRM-4	0.0868	3.6249	0.024
LDM-1	0.2144	3.4041	0.063
LDM-2	0.2346	3.4618	0.068
LDM-4	0.0730	2.9329	0.0249
LDMS-1	0.1159	4.2328	0.0274
LDMSM-1	0.0694	3.9936	0.0174
LRMS-1	0.1651	4.1961	0.0394
LRMSM-1	0.0355	4.0224	0.0088
NIST Obsidian	0.9268	1.3156	0.7045
NIST Obsidian	0.9117	1.2523	0.7280
NIST Obsidian -- NIST Values			0.7050

3.2.4 Phase II Glass Durability

The 7-day PCT durability of the Phase II glasses is shown in Figures 3.12 and 3.13 for sodium and silicon releases. The complete PCT results are tabulated in Appendix B. All the Phase II glasses were much more durable than the EA glasses. The highest 7-day PCT sodium releases were from LDM-0912 and LRM-0912, 1.2 and 1.02 $g/m^2/7d$. Compared with 6.6 $g/m^2/7d$, these glasses were still a factor of 6 more durable than EA glass. The most durable glasses were LDM-3, which had a sodium release of 0.29 $g/m^2/7d$, which was a factor of 23 more durable than EA glass. Within the LDM-glass group the durability order is:

LDM-3 > LDM-1 > LDM-5412 > LDM-4 > LDM-2 > LDM-0912.

The durability order for the LRM-glasses is:

LRM-3 > LRM-5412 > LRM-1 > LRM-4 > LRM-2 > LRM-0912.

The comparison between LRM-glass and LDM-glass is complicated. The durabilities for LDM-3, LDM-4, and LDM-1 are better than those of the corresponding LRM-3, LRM-4, and LRM-1. This may be an indication that the addition of F and Cl into glasses will be more beneficial than the addition of SO_3 and P_2O_5 under PCT test conditions, which are consistent with the results presented in Section 3.2. However, the durabilities for LDM-0912 and LDM-2 are worse than those of LRM-0912 and LRM-2, while both LDM-0912 and LRM-0912 are less durable than the base glass L5-0912. We interpret this to mean that the addition of either F and Cl or SO_3 and P_2O_5 into calcium oxide-containing glasses decreases glass durability and that the addition of F plus Cl is worse than the addition of SO_3 and P_2O_5. The durability of LDM-5412 and LRM-5412 was similar and was also similar to the durability of base glass L6-5412. This was probably due to the opposite effects with the addition of these minor components into boron-only glasses (improving durability) and into calcium-only glasses (decreasing durability) in a glass with almost equal amounts of boron and calcium oxides. These durability results on LRM-5412 and LDM-5412 were also consistent with the results discussed in Section 3.2, where opposite effects were observed with the addition of F and Cl and small effects were observed with the addition of SO_3 and P_2O_5.

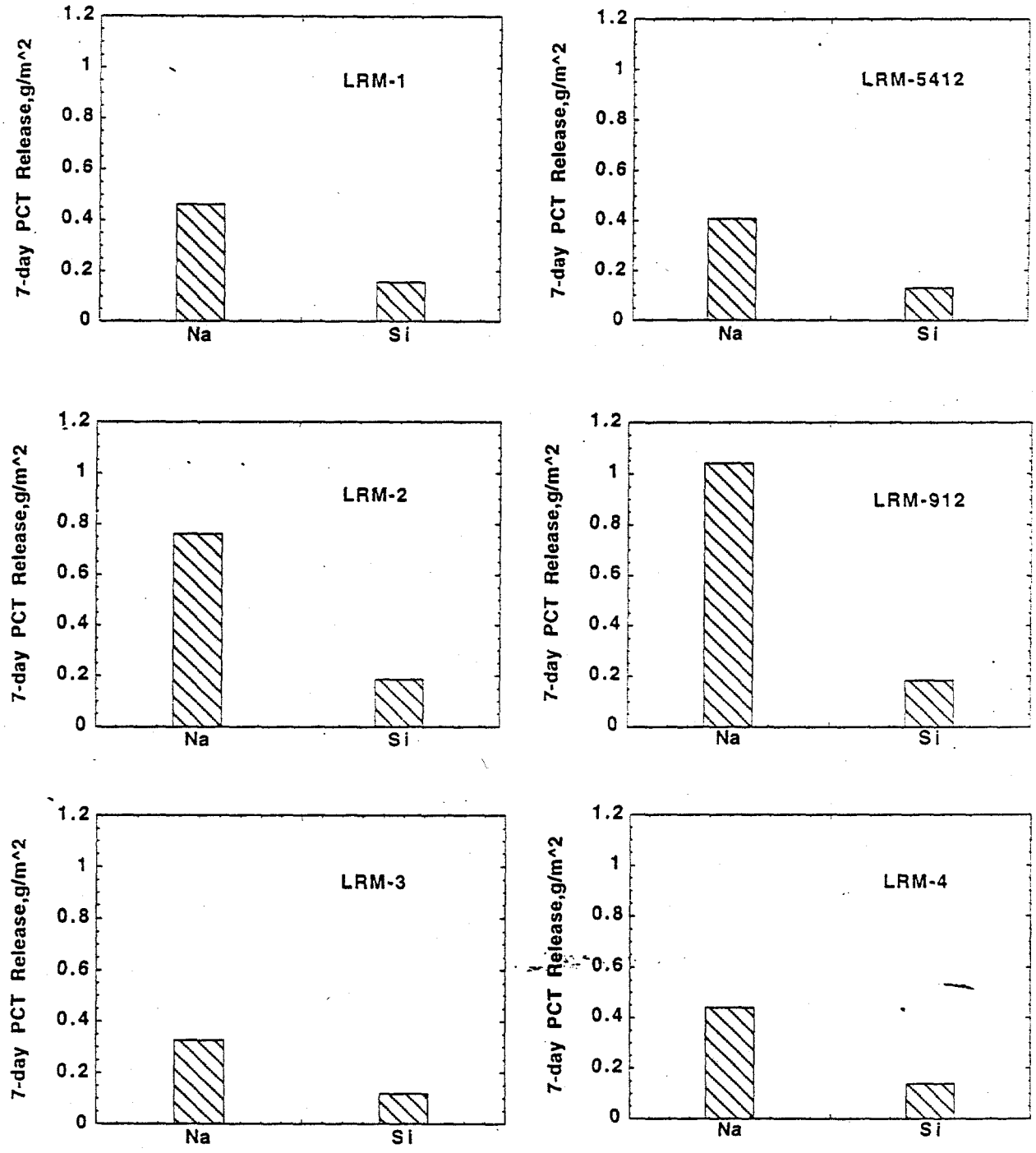


Figure 3.12 7-day PCT Results. Vendor glasses using M-DSSF wastes.

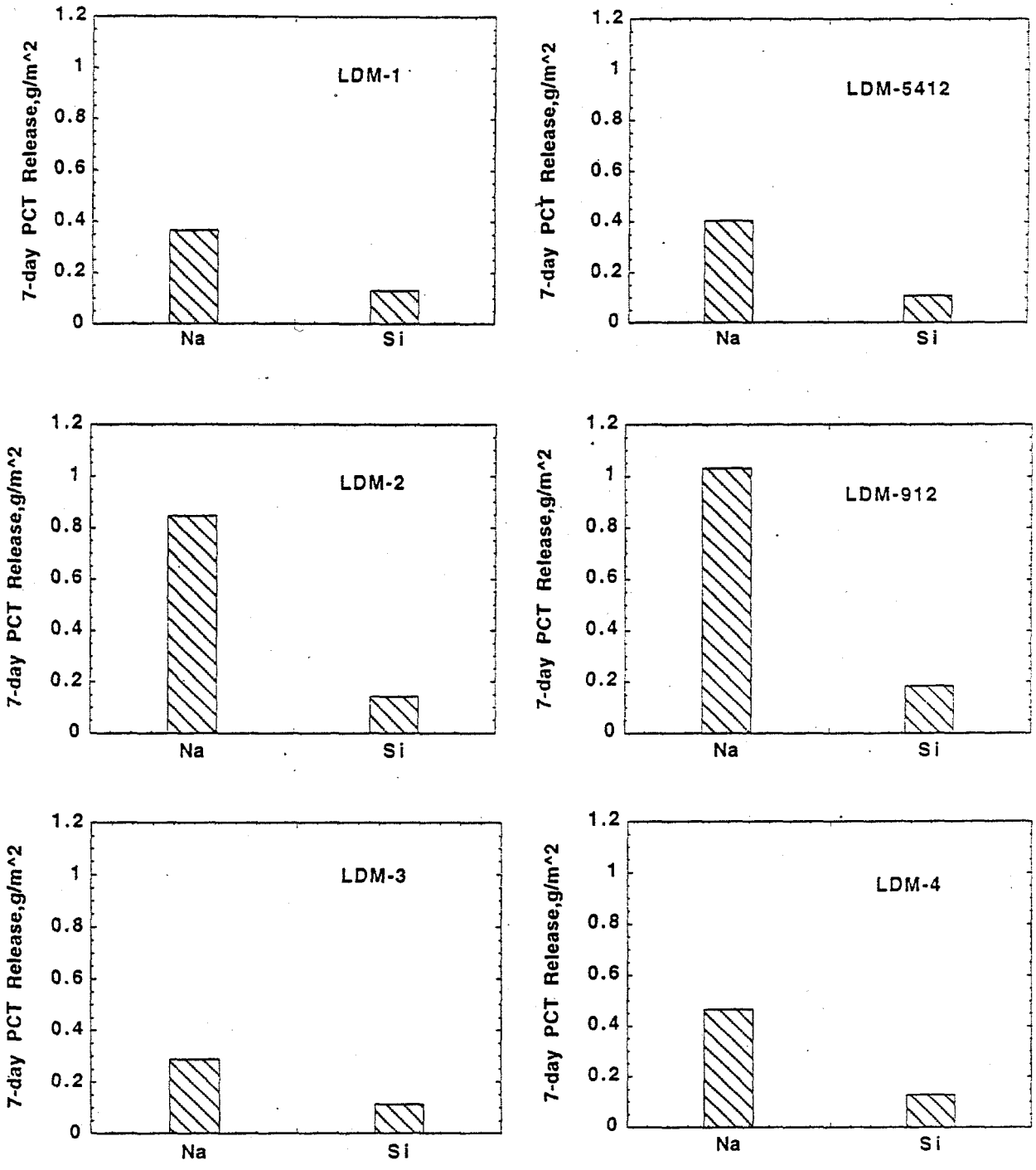


Figure 3.13 7-day PCT Results. Vendor glasses using M-RI wastes.

3.2.5 Phase II Glass Melting from Simulant Solutions

The Hanford LLW streams will likely be in the form of sludge after it is separated from high level waste. There is a need to explore the difference of glass melting from dry chemicals and sludge. The effort described below is one of such efforts. Only preliminary information was available when this report is prepared and the detailed discussion on this topic will be included in the year end report of the LLW glass formulation program.

Four compositions were prepared and melted with simulant waste slurries added as the "Others" component. The resulting glasses were characterized for chemical composition by ICP, durability by PCT, and viscosity. Two glasses, LRMS-1 and LRMSM-1, were based on the LRM-1 composition and two glasses, LRMS-1 and LRMSM-1, were based on the LDM-1 composition. The simulant solution (slurry) for the "Others" in the LRM-1 based compositions came from the M-RI simulant (Table 1.1) while the slurry of "Others" in LDM-1 based glass compositions was from the M-DSSF simulant (Table 1.1). The difference between LRMS-1 and LRMSM-1 is that LRMSM-1 has additional 3 wt% of metal ion mixture of Cu, Zn, Pb, Sn, Cr, Mn, Ni, Mo, Sb, As,Bi, and Cd although both were mad from simulant solutions. The same difference exists between LDMS-1 and LDMSM-1. The detailed nominal and analyzed compositions of these four glasses are in Appendix A2. The detailed procedure for the preparation of the simulant solutions and the metal mixture solutions are described in details in (Lokken-1995).

Each batch was made from dry chemicals, either oxide or carbonate, except for the "Others" mixture and the metal additions. Simulant solutions were agitated by either shaking the container vigorously or heating the solution on a hot plate and stirring with a impeller to dissolve particles. The solutions were then measured using a graduated cylinder and hand stirred into the dry chemicals in a 1L stainless steel beaker. The resulting slurry was smooth with a creamy consistency.

The slurries were dried in a convection oven heating from 120°C to approximately 200°C during the day occasionally checking the slurry for boiling. The samples were left, at a minimum, overnight at 200°C. They dried into a hard cake which was chipped out and put in a 500cc platinum crucible and placed in a melting furnace at 650°C. The temperature was increased at 50°C intervals until foaming occurred, between 800° and 850°C. The temperature was held steady while foaming to allow NOx to escape. At times, the sample would be removed from the furnace to cool and allow the foam to subside and often the foamed samples needed to be pushed back into the crucible with a

stainless steel rod. When the foam ceased to rise, the crucible was removed from the furnace, the temperature elevated to 1230° or 1250°C, and the crucible placed back into the furnace.

Melting was then conducted following the same procedure as described in Section 2.2. General observations of the melts are that all glasses except LDMS-1 had a yellow segregated phase on their surface after the final melt. This yellow substance was soluble in water. When contrasting simulant melts with dry chemical melts, the melt produced with simulants has more volatilization at melt temperature. Consequently, the viscosity is believed to increase the longer the melt was at temperature due to the continued volatilization. And all the glasses were black except for the segregated yellow layer.

LDMS-1 was initially melted at 1250°C but lowered to 1230°C shortly after the melt began due to low viscosity and high volatilization. No segregation of sulfur was observed. The viscosity was 10 Pa.S at 1376°C.

LDMSM-1 had the same starting composition as LDMS-1, but with the 3 wt% added metals. This glass was melted like LDMS-1 starting at 1250°C and then lowered to 1230°C. In both the first and second melts, a thin layer of yellow segregate was observed on the glass surface. Volatilization and foaming was more prevalent in this melt than LDMS-1. The viscosity was 10 Pa.S at 1323°C. Volatilization increased the viscosities of both LDMS glasses significantly during viscosity measurements.

LRMS-1 initially began its melt at 1230°C. During the second melt the volatilization was moderate and the glass appeared viscous so the temperature was raised to 1275°C. The viscosity was estimated to be 12 Pa.S at the final pour, but the measured viscosity was 10 Pa.S at 1338°C. A yellow segregated layer was observed in both first and second melts.

LRMSM-1 had the same initial composition as LRMS-1, but with 3 wt% added metals. This glass was melted at 1230°C. Both melts had a pool of yellow segregate. The segregate poured quickly from of the main melt and formed its own solid in two separate beads approximately 1cm diameter and 0.5mm thick. In addition, a yellow layer coated most of the surface of the poured glass. The viscosity was 10 Pa.S at 1297°C.

The redox states of these four glasses were analyzed in terms of the ratio of Fe(II) to total Fe as shown in Table 3.8. It was surprising to find that the glasses made from simulant solutions are more oxidizing, i.e., with lower Fe(II)/Fe ratio, than the glasses made from dry chemicals. The Fe(II)/Fe ratio of 0.0274 of LDMS-1 was only 43% of the value of 0.063 of LDM-1 (made from dry chemicals) and the ratio, 0.0394 of LRMS-1, was also only 53% of the 0.075 of LRM-1 (made from dry chemicals). The metal added glass had even lower Fe(II)/Fe ratios. These results may suggest a more oxidizing environment corrected by the simulant solutions during glass melting instead of the general perception that the simulant solution provides a more reducing condition.

The solubilities of SO_3 and P_2O_5 in these four glasses are tabulated in Table 3.9. It shows that LRMS-1 had higher SO_3 solubility than that of LRM-1, which is consistent with redox ratios discussed above, i.e., oxidized sulphur has higher solubility. The trend on phosphorus solubilities is not clear since the values in Table 3.9 are essentially within experimental errors.

The observed sulfur solubilities can be explained by the observed redox ratios but the increased foaming and sulphur segregation in the melting with simulant solutions are still not clear. The melting viscosities shown in Table 3.2 are basically the same for glasses made from dry chemicals and from simulant solutions. Very minor differences were also observed on glass durability (Appendix B2) between glasses made from dry chemicals and from simulant solutions.

Table 3.9. Sulfur and Phosphorus Contents in Phase II Simulant Glasses (wt%)

Glass	LRM-1	LRMS-1	LRMSM-1	LDM-1	LDMS-1	LDMSM-1
Nominal SO_3	1.01	1.01	1.01	0.21	0.21	0.21
Analyzed SO_3	0.76	0.96	0.70	0.22	0.32	0.26
Nominal P_2O_5	2.52	2.52	2.57	0.19	0.19	0.18
Analyzed P_2O_5	2.72	2.43	2.39	0.46	0.29	0.28

4.0 Conclusions and Recommendations

Phase II glass formulations were developed that can accommodate 2.5 wt% P_2O_5 and 1.0 wt% SO_3 and can be melted without significant processing problems under laboratory crucible conditions. These Phase II compositions are also a factor of 6 to 23 more durable than EA glasses. These glasses melted satisfactorily in temperature ranges from 1160° to 1410°C to suit different melting technologies. The compositions included boron-free glasses for those melters that prefer low-volatility formulations; boron-containing glasses for those melters that can reduce volatility through cold-cap and other operations; Zr-containing glasses for better long-term durability; and Fe-containing glasses for reducing melting viscosity and volatilization while maintaining chemical durability. The glasses made from simulated waste slurries were more prone to foaming and phase segregation, especially when the waste streams have high sulphur and phosphorus contents. The glasses made from slurry were more oxidized, i.e., with lower ratio of Fe(II)/(Total Fe), and had higher solubilities for sulphur (and similar solubility for phosphorus) than the glasses made from dry chemicals. The glasses made from dry chemicals and slurries have similar chemical durabilities and viscosities. The Phase II formulations were also demonstrated to be able to incorporate a total 3 wt% of metals of Cu, Zn, Pb, Sn, Cr, Mn, Ni, Mo, Sb, As, Bi, and Cd and the metal containing glasses were slightly less durable than those without metals..

Therefore, the Phase II formulations listed in Table 3.5 and 3.6 are suitable compositions to fulfill the needs of Phase II vendor testing and are recommended for use by Phase II vendors.

5.0 References

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Appendix A

Appendix A1. Phase I Vendor Glass Compositions

Vendor	Type	Glass ID	Al2O3	B2O3	CaO	Fe2O3	K2O	MgO	Na2O	SiO2	ZrO2
BCW	Analyzed	B1G9-011C4	12.15	1.41	5.16	0.44	3.71	0.25	12.05	63.87	0.08
BCW	Analyzed	B1G9-014C	12.60	1.62	5.22	0.58	2.84	0.24	13.37	62.56	0.06
BCW	Analyzed	B1G9-13C5	12.94	1.39	5.14	0.66	3.15	0.23	12.50	63.00	0.06
GDI	Analyzed	D1G4-002P	4.85	18.91	7.10	4.73	4.51	4.03	11.92	40.42	1.47
GDI	Analyzed	D1G4-009P	5.26	12.04	7.97	6.54	6.20	2.03	15.79	40.73	1.32
GDI	Analyzed	D1G4-017P	6.29	7.76	8.27	7.31	6.43	0.82	17.50	40.35	3.02
GDI	Analyzed	D1G4-022P2	6.70	7.36	8.69	7.77	2.46	0.61	18.00	42.47	3.62
GDI	Analyzed	D1G4-023P3	6.41	7.10	8.57	7.76	3.02	0.53	18.24	42.27	3.82
GDI	Analyzed	D1G4-026P4	6.49	6.66	8.50	7.82	3.83	0.42	18.22	41.83	4.01
GDI	Norminal	Duratek	6.14	6.15	7.80	7.50	3.68		18.82	42.23	5.09
PEI	Norminal	PEI	6.00		9.73	1.00	1.50	0.13	18.82	59.22	2.00
PNL	Norminal	LD4-912	12.00	9.00			1.46		20.00	55.91	
PNL	Norminal	LD5-912	12.00		9.00		1.46		20.00	55.91	
PNL	Norminal	LD6-5314	14.00	5.00	3.00		1.46		20.00	54.91	
PNL	Norminal	LD6-5412	12.00	5.00	4.00		1.46		20.00	55.91	
PNL	Analyzed	LD6-5412	12.17	5.05	4.12	0.11	1.66		20.41	55.44	0.08
PNL	Analyzed	SSHTM-3	11.63	6.09	4.14	0.02	1.04		22.55	52.81	0.34
PNL	Norminal	LD6-5510	10.00	5.00	5.00		1.46		20.00	56.91	
UBM	Analyzed	M1G1-008P	14.98	1.81	9.50	1.06		0.39	13.21	47.82	
UBM	Analyzed	M1G1-011P	13.35	2.53	6.75	1.16		0.30	15.24	50.53	
VTI	Analyzed	V1M2 6 32 011 P1	10.28	7.01	2.99	1.04	1.23	2.14	16.22	58.09	0.06
VTI	Analyzed	V1M2 6 32 040 P2	10.42	7.18	3.06	1.02	2.26	2.21	15.53	57.35	0.04
VTI	Analyzed	V1M2 6 34 015 P	10.76	7.24	3.03	1.04	1.36	2.21	16.29	57.22	0.05
VTI	Analyzed	V1M3 6 32 059 P1	10.62	7.29	3.33	1.04	2.00	2.21	15.97	56.69	0.05
VTI	Analyzed	V1M3 6 32 075 P2	10.98	7.61	3.51	1.14	1.81	2.28	12.67	59.08	0.03
VTI	Analyzed	V1M3 6 34 071 P	16.92	6.84	3.02	0.96	1.71	2.08	14.85	52.98	0.04
VTI	Analyzed	V1M4 6 32 088 P1	10.59	7.33	3.35	1.20	2.02	2.13	16.80	55.63	0.04
VTI	Analyzed	V1M4 6 32 096 P2	10.87	7.52	2.99	0.99	2.12	2.15	16.54	55.97	0.04
VTI	Norminal	Vectra	10.00	8.00	2.90	1.00	1.46	2.10	20.00	52.90	
VTI	Analyzed	Vectra	9.45	8.20	2.90	1.10	0.91	1.87	20.82	53.31	0.02
VTI	Analyzed	Vectra I	10.11	8.11	2.93	1.08	1.48	1.85	21.37	51.81	
WSTC	Norminal	WSTC	18.22	9.45	4.65		1.44		18.82	42.90	2.10

Appendix A1. Phase I Vendor Glass Compositions(Continued)

Vendor	Type	Glass ID	BaO	CeO2	Cr2O3	Li2O	MnO	MoO3	Nd2O3	NiO	P2O5	SO3	SrO	TiO2	ZnO
BCW	Analyzed	B1G9-011C4	0.01		0.05	0.00	0.02	0.06	0.08	0.04			0.10	0.19	0.14
BCW	Analyzed	B1G9-014C	0.01		0.05		0.02	0.07	0.13	0.04			0.10	0.17	0.19
BCW	Analyzed	B1G9-13C5	0.01		0.05	0.00	0.02	0.06	0.11	0.04			0.10	0.17	0.12
GDI	Analyzed	D1G4-002P	0.32	0.04	0.31	0.04	0.06	0.03	0.10	0.19		0.21	0.03	0.21	0.31
GDI	Analyzed	D1G4-009P	0.15	0.05	0.25	0.02	0.03	0.10	0.11	0.13		0.23	0.07	0.62	0.17
GDI	Analyzed	D1G4-017P	0.06	0.07	0.18		0.02	0.14	0.11	0.08		0.22	0.09	0.81	0.18
GDI	Analyzed	D1G4-022P2	0.04	0.07	0.21		0.02	0.15	0.05	0.06	0.06	0.21	0.10	0.89	0.21
GDI	Analyzed	D1G4-023P3	0.04	0.04	0.19		0.02	0.15	0.03	0.07	0.04	0.21	0.10	0.91	0.27
GDI	Analyzed	D1G4-026P4	0.03	0.12	0.15		0.02	0.15	0.09	0.04	0.05	0.23	0.10	0.90	0.17
GDI	Norminal	Duratek			0.04			0.15			0.19	0.21	0.10	1.00	
PEI	Norminal	PEI			0.04			0.15			0.19	0.21	0.10		
PNL	Norminal	LD4-912													
PNL	Norminal	LD5-912													
PNL	Norminal	LD6-5314													
PNL	Norminal	LD6-5412													
PNL	Analyzed	LD6-5412			0.05072	0.01	0.01	0.13	0.06	0.03	0.22	0.18	0.09	0.02	0.14
PNL	Analyzed	SSHTM-3			0.16387	0.02	0.01	0.14	0.02	0.03	0.31	0.29	0.07	0.07	0.26
PNL	Norminal	LD6-5510													
UBM	Analyzed	M1G1-008P						0.07						0.68	
UBM	Analyzed	M1G1-011P						0.09						0.35	
VTI	Analyzed	V1M2 6 32 011 P1			0.31		0.01	0.22	0.02	0.04			0.06	0.01	0.08
VTI	Analyzed	V1M2 6 32 040 P2		0.01	0.29		0.01	0.19	0.04	0.04			0.06	0.01	0.06
VTI	Analyzed	V1M2 6 34 015 P		0.01	0.31		0.01	0.21	0.07	0.04			0.06	0.02	
VTI	Analyzed	V1M3 6 32 059 P1		0.06	0.27		0.01	0.16	0.10	0.04			0.08	0.01	0.07
VTI	Analyzed	V1M3 6 32 075 P2	0.01	0.06	0.29	0.01	0.02	0.16	0.09	0.04			0.08	0.02	0.08
VTI	Analyzed	V1M3 6 34 071 P			0.25		0.01	0.15	0.06	0.03			0.06	0.03	
VTI	Analyzed	V1M4 6 32 088 P1	0.01	0.05	0.31	0.03	0.03	0.13	0.09	0.04			0.09	0.02	0.08
VTI	Analyzed	V1M4 6 32 096 P2			0.30		0.01	0.13	0.06	0.03			0.08	0.01	
VTI	Norminal	Vectra													
VTI	Analyzed	Vectra			0.04			0.15	0.03	0.03	0.40	0.22	0.11		0.28
VTI	Analyzed	Vectra I			0.04			0.15	0.01		0.64		0.11	0.01	0.28
WSTC	Norminal	WSTC				0.83									

Appendix A2. Phase II Vendor Glass Compositions(Continued)

Vendor	Type	Glass ID	CeO2	Cl	Cr2O3	Cs2O	F	I	Li2O	MnO	MoO3	Nd2O3	NiO	P2O5	SO3	SrO	TiO2	ZnO	Other
PNL	Norminal	LDM-0912		0.64	0.04	0.14	0.82	0.13		0.00	0.15			0.19	0.21	0.10			
PNL	Analyzed	LDM-0912	0.06								0.16			0.24	0.26	0.12			
PNL	Norminal	LDM-1		0.64	0.04	0.14	0.82	0.13		0.00	0.15			0.19	0.21	0.10			
PNL	Analyzed	LDM-1	0.05		0.05					0.01	0.15	0.05		0.46	0.22	0.10	0.01	0.11	
PNL	Norminal	LDM-2		0.64	0.04	0.14	0.82	0.13		0.00	0.15			0.19	0.21	0.10			
PNL	Analyzed	LDM-2			0.05						0.15	0.06		0.28	0.23	0.11		0.06	
PNL	Norminal	LDM-3		0.64	0.04	0.14	0.82	0.13		0.00	0.15			0.19	0.21	0.10			
PNL	Analyzed	LDM-3	0.08		0.05						0.16	0.07	0.05	0.28	0.21	0.12	0.01	0.08	
PNL	Norminal	LDM-4		0.64	0.04	0.14	0.82	0.13		0.00	0.15			0.19	0.21	0.10			
PNL	Analyzed	LDM-4			0.05					0.01	0.15	0.08	0.03	0.27	0.26	0.12		0.14	
PNL	Norminal	LDM-5412		0.64	0.04	0.14	0.82	0.13		0.00	0.15			0.19	0.21	0.10			
PNL	Analyzed	LDM-5412			0.05						0.16	0.06		0.62	0.69	0.11	0.01	0.16	
PNL	Norminal	LDMS-1		0.64	0.04	0.14	0.82	0.13		0.00	0.14			0.19	0.21	0.10			
PNL	Analyzed	LDMS-1	0.05		0.03				0.01	0.01	0.13	0.08	0.02	0.28	0.26	0.09	0.02	0.06	
PNL	Norminal	LDMSM-1		0.62	0.26	0.14	0.79	0.12		0.20	0.69		0.46	0.18	0.21	0.10		0.45	1.87*
PNL	Analyzed	LDMSM-1	0.05		0.17				0.01	0.23	0.30	0.10	0.48	0.30	0.27	0.10	0.02	0.49	
PNL	Norminal	LRM-0912		0.04	0.04	0.15	0.26	0.14		0.01	0.15			2.52	1.01	0.11			
PNL	Analyzed	LRM-0912	0.05		0.04					0.01	0.16	0.09		2.67	1.01	0.13		0.10	
PNL	Norminal	LRM-1		0.04	0.04	0.15	0.26	0.14	1.00	0.01	0.15			2.52	1.01	0.11			
PNL	Analyzed	LRM-1			0.04				1.02	0.02	0.15			2.72	0.76	0.12	0.02	0.21	
PNL	Norminal	LRM-2		0.04	0.04	0.15	0.26	0.14		0.01	0.15			2.52	1.01	0.11			
PNL	Analyzed	LRM-2			0.04					0.02	0.16	0.03		2.52	0.74	0.12	0.01	0.18	
PNL	Norminal	LRM-3		0.04	0.04	0.15	0.26	0.14		0.01	0.15			2.52	1.01	0.11			
PNL	Analyzed	LRM-3			0.04					0.01	0.17	0.04		2.82	0.59	0.13	0.01	0.24	
PNL	Norminal	LRM-4		0.04	0.04	0.15	0.26	0.14	0.50	0.01	0.15			2.52	1.01	0.11			
PNL	Analyzed	LRM-4	0.06		0.04				0.49	0.02	0.15	0.09	0.02	2.62	0.93	0.12	0.01	0.09	
PNL	Norminal	LRM-5412		0.04	0.04	0.15	0.26	0.14		0.01	0.15			2.52	1.01	0.11			
PNL	Analyzed	LRM-5412	0.05		0.04					0.01	0.16	0.08	0.03	2.67	0.87	0.13		0.11	
PNL	Norminal	LRMS-1		0.04	0.04	0.15	0.26	0.14	1.00	0.01	0.15			2.52	1.01	0.11			
PNL	Analyzed	LRMS-1	0.05		0.03				1.01	0.01	0.15	0.10	0.02	2.57	1.01	0.11	0.02	0.06	
PNL	Norminal	LRMSM-1		0.03	0.25	0.15	0.25	0.13	0.96	0.20	0.69		0.46	2.43	0.97	0.11		0.45	1.87*
PNL	Analyzed	LRMSM-1	0.07		0.21				0.95	0.24	0.43	0.12	0.49	2.57	0.76	0.11	0.02	0.49	

* Others in clude Bi2O3, CdO, PbO, Sb2O3, CuO, SnO, As2O3

Appendix A2. Phase II Vendor Glass Compositions

Vendor	Type	Glass ID	Al2O3	B2O3	CaO	Fe2O3	K2O	MgO	Na2O	SiO2	ZrO2
PNL	Norminal	LDM-0912	12.00		9.00	0.00	1.43	0.00	20.00	55.14	
PNL	Analyzed	LDM-0912	12.22		9.60	0.06	1.67	0.10	19.92	55.30	
PNL	Norminal	LDM-1	12.00	2.00	2.00	6.00	1.43	0.00	20.00	50.14	4.00
PNL	Analyzed	LDM-1	12.17	2.01	1.78	6.21	1.46		21.05	50.06	4.02
PNL	Norminal	LDM-2	12.00		6.00	6.00	1.43	0.00	20.00	52.14	
PNL	Analyzed	LDM-2	12.08		6.24	6.19	1.79		20.30	51.87	0.01
PNL	Norminal	LDM-3	12.00	6.00	0.00	0.00	1.43	0.00	20.00	52.14	6.00
PNL	Analyzed	LDM-3	12.44	6.31	0.12	0.05	2.30		18.85	53.50	5.27
PNL	Norminal	LDM-4	10.00	6.00	6.00	6.00	1.43	0.00	20.00	44.14	4.00
PNL	Analyzed	LDM-4	10.06	6.25	6.48	6.14	2.02		20.36	43.70	3.82
PNL	Norminal	LDM-5412	12.00	5.00	4.00	0.00	1.43	0.00	20.00	55.14	
PNL	Analyzed	LDM-5412	12.05	5.01	3.94	0.06	2.13	0.15	21.22	53.56	
PNL	Norminal	LDMS-1	12.00	2.00	2.00	6.00	1.43	0.00	20.00	50.14	4.00
PNL	Analyzed	LDMS-1	12.13	2.03	2.05	6.07	2.50	0.11	20.83	48.03	4.05
PNL	Norminal	LDMSM-1	11.55	1.93	1.93	5.78	1.38		19.25	48.26	3.85
PNL	Analyzed	LDMSM-1	11.77	1.93	2.12	5.76	2.71	0.11		46.91	
PNL	Norminal	LRM-0912	12.00		9.00	0.00	0.03		20.00	54.54	
PNL	Analyzed	LRM-0912	11.79	0.03	9.41	0.05	0.70	0.12	20.42	53.19	
PNL	Norminal	LRM-1	12.00	2.00	2.00	6.00	0.03		20.00	48.54	4.00
PNL	Analyzed	LRM-1	12.19	2.02	1.82	6.24			21.23	47.42	3.99
PNL	Norminal	LRM-2	12.00		6.00	6.00	0.03		20.00	51.54	
PNL	Analyzed	LRM-2	11.41		6.13	5.87		0.11	22.13	48.20	
PNL	Norminal	LRM-3	12.00	6.00	0.00	0.00	0.03		20.00	51.54	6.00
PNL	Analyzed	LRM-3	12.62	6.38	0.19	0.05	0.44		18.11	55.29	5.07
PNL	Norminal	LRM-4	10.00	6.00	6.00	6.00	0.03		20.00	43.04	4.00
PNL	Analyzed	LRM-4	9.77	6.01	6.19	5.98	1.46	0.11	20.22	41.74	3.82
PNL	Norminal	LRM-5412	12.00	5.00	4.00	0.00	0.03		20.00	54.54	
PNL	Analyzed	LRM-5412	11.86	5.09	4.23	0.05	0.92		20.27	53.41	
PNL	Norminal	LRMS-1	12.00	2.00	2.00	6.00	0.03		20.00	48.54	4.00
PNL	Analyzed	LRMS-1	11.91	2.01	2.20	5.98	1.76	0.11		47.17	
PNL	Norminal	LRMSM-1	11.55	1.93	1.93	5.78	0.03		19.25	46.72	3.85
PNL	Analyzed	LRMSM-1	11.44	1.90	2.12	5.73	2.44	0.13		44.99	

Appendix B

B1 7-Day PCT Elemental Releases (g/m^2) of Phase I Vendor Glasses

B2 7-Day PCT Elemental Releases (g/m^2) of Phase II Vendor Glasses

Appendix B1. 7-Day PCT Elemental Release (g/m²) of Phase I Vendor Glasses

Vendor	Glass ID	Comp. Used	pH	Al2O3	B2O3	CaO	Fe2O3	K2O	MgO	Na2O	SiO2
BCW	B1G9-005 C	Anal. B1G9-014C	10.52	0.051	0.065	0.035	0.002			0.142	0.048
BCW	B1G9-005 D	Anal. B1G9-014C	10.56	0.051	0.066	0.034	0.002			0.146	0.048
BCW	B1G9-006 C	Anal. B1G9-014C	10.61	0.057	0.065	0.035	0.002			0.153	0.047
BCW	B1G9-006 D	Anal. B1G9-014C	10.57	0.056	0.065	0.035	0.002			0.153	0.047
BCW	B1G9-008 C	Anal. B1G9-014C	10.21	0.055	0.031	0.027	0.004			0.095	0.040
BCW	B1G9-008 D	Anal. B1G9-014C	10.23	0.055	0.031	0.026	0.004			0.097	0.040
BCW	B1G9-011 C	Anal. B1G9-014C	10.37	0.040	0.049	0.034	0.001			0.124	0.050
BCW	B1G9-011 D	Anal. B1G9-014C	10.36	0.040	0.049	0.034	0.001			0.126	0.050
BCW	B1G9-013 C	Anal. B1G9-014C	10.6	0.047	0.065	0.036	0.002			0.160	0.052
BCW	B1G9-013 D	Anal. B1G9-014C	10.64	0.046	0.064	0.035	0.004			0.155	0.051
BCW	B1G9-014 C	Anal. B1G9-014C	10.44	0.043	0.045	0.033	0.002			0.125	0.049
BCW	B1G9-014 D	Anal. B1G9-014C	10.45	0.043	0.045	0.033	0.004	0.007		0.123	0.049
GDI	D1G4-022P2 C	Norminal	11.46	0.080	0.534	0.006	0.000	0.353		0.619	0.167
GDI	D1G4-022P2 D	Norminal	11.45	0.080	0.542	0.006	0.000	0.368		0.621	0.168
GDI	D1G4-023P3 C	Norminal	11.46	0.086	0.502	0.005	0.000	0.345		0.610	0.167
GDI	D1G4-023P3 D	Norminal	11.45	0.085	0.500	0.005	0.000	0.339		0.606	0.166
PEI	PEI-(A) C	Norminal	12.12	0.193		0.016	0.004	0.555	0.070	1.684	0.250
PEI	PEI-(B) D	Norminal	12.16	0.201		0.018	0.004	0.685	0.147	1.708	0.265
PNL	LD4-912 C	Norminal	10.56	0.126	0.352			0.165		0.314	0.127
PNL	LD4-912 D	Norminal	10.53	0.124	0.351			0.083		0.317	0.127
PNL	LD5-912 C	Norminal	12.02	0.216		0.013		0.330		1.240	0.224
PNL	LD5-912 D	Norminal	12.04	0.217		0.013		0.289		1.217	0.224
PNL	LD6-5314 C	Norminal	11.05	0.086	0.099	0.028		0.083		0.253	0.090
PNL	LD6-5314 D	Norminal	11.05	0.086	0.098	0.028		0.083		0.260	0.090
PNL	LD6-5412 C	Norminal	11.37	0.097	0.111	0.050		0.083		0.371	0.104
PNL	LD6-5412 D	Norminal	11.4	0.098	0.113	0.050		0.083		0.381	0.105
PNL	LD6-5510 C	Norminal	11.62	0.111	0.130	0.066		0.083		0.529	0.120
PNL	LD6-5510 D	Norminal	11.33	0.110	0.136	0.063		0.413		0.505	0.118
PNL	LD6-5510 D	Norminal		0.112	0.131	0.068		0.206		0.519	0.121
PNL	SSHTM-3 C	Norm. LD6-5412	11.36	0.110	0.174	0.028		0.106		0.444	0.119
PNL	SSHTM-3 D	Norm. LD6-5413	11.29	0.109	0.173	0.028		0.114		0.433	0.118

Appendix B1. 7-Day PCT Elemental Release (g/m²) of Phase I Vendor Glasses (Continued)

Vendor	Glass ID	Comp. Used	pH	Cr2O3	Li2O	MnO	MoO3	Nd2O3	P2O5	SO3	SrO	ZrO2
BCW	B1G9-005 C	Anal. B1G9-014C	10.52				0.057				0.018	
BCW	B1G9-005 D	Anal. B1G9-014C	10.56				0.057				0.018	
BCW	B1G9-006 C	Anal. B1G9-014C	10.61				0.057				0.018	
BCW	B1G9-006 D	Anal. B1G9-014C	10.57				0.057				0.018	
BCW	B1G9-008 C	Anal. B1G9-014C	10.21				0.034				0.012	
BCW	B1G9-008 D	Anal. B1G9-014C	10.23				0.023				0.012	
BCW	B1G9-011 C	Anal. B1G9-014C	10.37				0.034				0.018	
BCW	B1G9-011 D	Anal. B1G9-014C	10.36				0.045				0.018	
BCW	B1G9-013 C	Anal. B1G9-014C	10.6				0.057				0.018	
BCW	B1G9-013 D	Anal. B1G9-014C	10.64				0.057				0.018	
BCW	B1G9-014 C	Anal. B1G9-014C	10.44				0.045				0.018	
BCW	B1G9-014 D	Anal. B1G9-014C	10.45				0.045				0.018	
GDI	D1G4-022P2 C	Norminal	11.46	0.110			0.360		0.199	0.363		
GDI	D1G4-022P2 D	Norminal	11.45	0.110			0.365		0.199	0.369		
GDI	D1G4-023P3 C	Norminal	11.46	0.110			0.360		0.283	0.345		
GDI	D1G4-023P3 D	Norminal	11.45	0.110			0.360		0.289	0.339		
PEI	PEI-(A) C	Norminal	12.12	0.073			0.355		0.103	0.297	0.024	
PEI	PEI-(B) D	Norminal	12.16	0.110			0.390		0.133	0.339	0.030	0.001
PNL	LD4-912 C	Norminal	10.56									
PNL	LD4-912 D	Norminal	10.53									
PNL	LD5-912 C	Norminal	12.02									
PNL	LD5-912 D	Norminal	12.04									
PNL	LD6-5314 C	Norminal	11.05									
PNL	LD6-5314 D	Norminal	11.05									
PNL	LD6-5412 C	Norminal	11.37									
PNL	LD6-5412 D	Norminal	11.4									
PNL	LD6-5510 C	Norminal	11.62									
PNL	LD6-5510 D	Norminal	11.33									
PNL	LD6-5510 D	Norminal										
PNL	SSHTM-3 C	Norm. LD6-5412	11.36									
PNL	SSHTM-3 D	Norm. LD6-5413	11.29									

Appendix B1. 7-Day PCT Elemental Release (g/m²) of Phase I Vendor Glasses (Continued)

Vendor	Glass ID	Comp. Used	pH	Al2O3	B2O3	CaO	Fe2O3	K2O	MgO	Na2O	SiO2
UBM	M1G1-008P C	Analyzed	10.27	0.05	0.08	0.05				0.22	0.06
UBM	M1G1-008P D	Analyzed	10.8	0.05	0.08	0.05				0.22	0.06
UBM	M1G1-011P C	Analyzed	11.06	0.06	0.10	0.05				0.32	0.08
UBM	M1G1-011P D	Analyzed	11.06	0.06	0.10	0.05				0.32	0.08
VTI	V1M2 6 32 011 P1C	Analyzed	10.27	0.060	0.134	0.011	0.003	0.084	0.005	0.214	0.094
VTI	V1M2 6 32 011 P1D	Analyzed	10.32	0.060	0.133	0.011	0.003	0.087	0.004	0.212	0.094
VTI	V1M2 6 32 040 P2C	Analyzed	10.23	0.054	0.129	0.013	0.002	0.057	0.004	0.190	0.087
VTI	V1M2 6 32 040 P2D	Analyzed	10.2	0.054	0.129	0.013	0.002	0.056	0.004	0.189	0.087
VTI	V1M3 6 32 059 P1C	Analyzed	10.33	0.059	0.144	0.010	0.003	0.077	0.004	0.219	0.095
VTI	V1M3 6 32 059 P1D	Analyzed	10.35	0.061	0.149	0.011	0.003	0.058	0.004	0.227	0.097
VTI	V1M3 6 32 075 P2C	Analyzed	10.32	0.056	0.131	0.011	0.003	0.068	0.005	0.264	0.088
VTI	V1M3 6 32 075 P2D	Analyzed	10.31	0.056	0.129	0.011	0.003	0.071	0.004	0.260	0.087
VTI	V1M4 6 32 088 P1C	Analyzed	10.38	0.059	0.142	0.012	0.001	0.073	0.003	0.213	0.094
VTI	V1M4 6 32 088 P1D	Analyzed	10.37	0.059	0.141	0.012	0.002	0.084	0.004	0.210	0.093
VTI	V1M4 6 32 096 P2C	Analyzed	10.37	0.059	0.148	0.011	0.002	0.063	0.003	0.219	0.096
VTI	V1M4 6 32 096 P2D	Analyzed	10.37	0.059	0.148	0.012	0.002	0.069	0.004	0.218	0.096
VTI	Vectra C	Analyzed	11.11	0.130	0.451	0.012	0.036	0.199	0.040	0.540	0.182
VTI	Vectra D	Analyzed	11.12	0.133	0.470	0.012	0.039	0.235	0.045	0.557	0.187
WSTC	WSTC C	Norminal		0.085	0.149	0.003				0.240	0.082
WSTC	WSTC C	Norminal	10.82	0.088	0.152	0.006		0.114		0.246	0.086
WSTC	WSTC D	Norminal	10.81	0.088	0.153	0.006		0.110		0.246	0.086

Appendix B1. 7-Day PCT Elemental Release (g/m²) of Phase I Vendor Glasses (Continued)

Vendor	Glass ID	Comp. Used	pH	Cr2O3	Li2O	MnO	MoO3	Nd2O3	P2O5	SO3	SrO	ZrO2
UBM	M1G1-008P C	Analyzed	10.27				1.07					
UBM	M1G1-008P D	Analyzed	10.8				1.07					
UBM	M1G1-011P C	Analyzed	11.06				1.11					
UBM	M1G1-011P D	Analyzed	11.06				1.14					
VTI	V1M2 6 32 011 P1C	Analyzed	10.27	0.009			0.125	0.074			0.008	
VTI	V1M2 6 32 011 P1D	Analyzed	10.32	0.009			0.126	0.083			0.008	
VTI	V1M2 6 32 040 P2C	Analyzed	10.23	0.009			0.122	0.065			0.008	
VTI	V1M2 6 32 040 P2D	Analyzed	10.2	0.009			0.122	0.067			0.008	
VTI	V1M3 6 32 059 P1C	Analyzed	10.33	0.011			0.159	0.027			0.007	
VTI	V1M3 6 32 059 P1D	Analyzed	10.35	0.011			0.164	0.015			0.007	
VTI	V1M3 6 32 075 P2C	Analyzed	10.32	0.011			0.211	0.019			0.007	
VTI	V1M3 6 32 075 P2D	Analyzed	10.31	0.011			0.210	0.022			0.008	
VTI	V1M4 6 32 088 P1C	Analyzed	10.38	0.015			0.347	0.024			0.008	
VTI	V1M4 6 32 088 P1D	Analyzed	10.37	0.016			0.358	0.032			0.008	
VTI	V1M4 6 32 096 P2C	Analyzed	10.37	0.012			0.216	0.026			0.007	
VTI	V1M4 6 32 096 P2D	Analyzed	10.37	0.013			0.216	0.035			0.007	
VTI	Vectra C	Analyzed	11.11									
VTI	Vectra D	Analyzed	11.12									
WSTC	WSTC C	Norminal			0.079							
WSTC	WSTC C	Norminal	10.82		0.080							0.001
WSTC	WSTC D	Norminal	10.81		0.079							0.001

Appendix B2. 7-Day PCT Elemental Release (g/m²) of Phase II Vendor Glasses

Vendor	Glass ID	Comp. Used	pH	Al2O3	B2O3	CaO	Fe2O3	K2O	MgO	Na2O	SiO2
PNL	LDM-0912C	Norminal	11.81	0.212		0.015		0.361		1.204	0.220
PNL	LDM-0912D	Norminal	11.82	0.209		0.014		0.375		1.190	0.217
PNL	LDM-1C	Norminal	11.12	0.138	0.173		0.020	0.147		0.365	0.131
PNL	LDM-1D	Norminal	11.12	0.136	0.172		0.020	0.141		0.365	0.131
PNL	LDM-2C	Norminal	10.66	0.137		0.013	0.005	0.215		0.772	0.143
PNL	LDM-2D	Norminal	10.67	0.170		0.017	0.006	0.266		0.917	0.142
PNL	LDM-3C	Norminal	10.66	0.115	0.162		1.227	0.058		0.282	0.110
PNL	LDM-3D	Norminal	10.67	0.117	0.169		1.346	0.087		0.293	0.112
PNL	LDM-4C	Norminal	10.93	0.116	0.281		0.005	0.240		0.464	0.130
PNL	LDM-4D	Norminal	10.96	0.113	0.282		0.006	0.230		0.462	0.128
PNL	LDM-5412C	Norminal	10.93	0.101	0.125	0.039		0.158		0.388	0.109
PNL	LDM-5412D	Norminal	10.96	0.109	0.127	0.041		0.121		0.421	0.109
PNL	LDMS-1C	Analyzed	10.89	0.129	0.153	0.011	0.019	0.056		0.305	0.125
PNL	LDMS-1D	Analyzed	10.92	0.131	0.155	0.010	0.020	0.053		0.306	0.126
PNL	LDMSM-1C	Analyzed	11.09	0.153	0.192	0.007	0.013	0.062		0.386	0.145
PNL	LDMSM-1D	Analyzed	11.11	0.153	0.193	0.005	0.013	0.063		0.389	0.146
PNL	LRM-0912C	Norminal	11.71	0.162		0.026		2.385		1.020	0.182
PNL	LRM-0912D	Norminal	11.75	0.168		0.024		2.835		1.039	0.187
PNL	LRM-1C	Norminal	11.22	0.163	0.206		0.024	2.087		0.466	0.155
PNL	LRM-1D	Norminal	11.23	0.160	0.203		0.024	2.592		0.458	0.153
PNL	LRM-2C	Norminal	11.50	0.179		0.006	0.015	3.011		0.716	0.184
PNL	LRM-2D	Norminal	11.49	0.206		0.007	0.016	3.649		0.807	0.186
PNL	LRM-3C	Norminal	10.85	0.122	0.163		0.758	1.659		0.325	0.118
PNL	LRM-3D	Norminal	10.86	0.149	0.164		0.758	1.586		0.392	0.118
PNL	LRM-4C	Norminal	11.19	0.135	0.283		0.006	2.195		0.468	0.148
PNL	LRM-4D	Norminal	11.19	0.134	0.290		0.006	2.542		0.472	0.149
PNL	LRM-5412C	Norminal	10.97	0.146	0.152	0.008				0.409	0.132
PNL	LRM-5412D	Norminal	10.98	0.130	0.155	0.006		0.908		0.372	0.135
PNL	LRMS-1C	Analyzed	11.23	0.165	0.205	0.009	0.015	0.000		0.444	0.159
PNL	LRMS-1D	Analyzed	11.23	0.165	0.205	0.008	0.015	0.000		0.445	0.159
PNL	LRMSM-1C	Analyzed	11.30	0.187	0.248	0.006	0.010	0.000		0.512	0.180
PNL	LRMSM-1D	Analyzed	11.30	0.186	0.247	0.006	0.010	0.000		0.509	0.180

Appendix B2. 7-Day PCT Elemental Release (g/m²) of Phase II Vendor Glasse (Continued)

Vendor	Glass ID	Comp. Used	pH	Cr2O3	Li2O	MnO	MoO3	Nd2O3	P2O5	SO3	SrO	ZrO2	CuO	SO4	CdO	NiO	ZnO
PNL	LDM-0912C	Norminal	11.81	0.091			0.298		1.524	0.272	0.040						
PNL	LDM-0912D	Norminal	11.82	0.092			0.294		1.742	0.272	0.038						
PNL	LDM-1C	Norminal	11.12				0.162		0.529	0.148	0.005	0.009					
PNL	LDM-1D	Norminal	11.12				0.163		0.514	0.148	0.005	0.009					
PNL	LDM-2C	Norminal	10.66				0.180		0.652	0.154	0.010						
PNL	LDM-2D	Norminal	10.67				0.192		0.851	0.119	0.012						
PNL	LDM-3C	Norminal	10.66	0.098		0.112	0.123		0.911	0.067	0.016	0.073					
PNL	LDM-3D	Norminal	10.67	0.104		0.123	0.128		0.888	0.070	0.016	0.074					
PNL	LDM-4C	Norminal	10.93				0.243		1.477	0.273							
PNL	LDM-4D	Norminal	10.96				0.241		1.484	0.266	0.002	0.000					
PNL	LDM-5412C	Norminal	10.93				0.121		0.901	0.079	0.024						
PNL	LDM-5412D	Norminal	10.96				0.123		1.056	0.067	0.026						
PNL	LDMS-1C	Analyzed	10.89				0.138		0.174			0.009					
PNL	LDMS-1D	Analyzed	10.92				0.138		0.110			0.009					
PNL	LDMSM-1C	Analyzed	11.09	0.014	0.000	0.006	0.153		0.115			0.005	0.013	0.070	0.005	0.007	0.012
PNL	LDMSM-1D	Analyzed	11.11	0.014	0.000	0.009	0.155		0.102			0.005	0.013	0.064	0.005	0.007	0.014
PNL	LRM-0912C	Norminal	11.71	0.070			0.214		0.046	0.203	0.038						
PNL	LRM-0912D	Norminal	11.75	0.073			0.221		0.054	0.209	0.038						
PNL	LRM-1C	Norminal	11.22		0.106	0.026	0.230		0.194	0.179	0.007	0.006					
PNL	LRM-1D	Norminal	11.23		0.104	0.028	0.226		0.191	0.175	0.007	0.004					
PNL	LRM-2C	Norminal	11.50	0.049			0.256		0.113	0.185	0.007						
PNL	LRM-2D	Norminal	11.49	0.055		0.022	0.275		0.095	0.174	0.008						
PNL	LRM-3C	Norminal	10.85	0.105		0.061	0.205		0.075	0.120	0.017	0.005					
PNL	LRM-3D	Norminal	10.86	0.105		0.061	0.255		0.065	0.115	0.017	0.009					
PNL	LRM-4C	Norminal	11.19		0.133		0.250		0.206	0.249							
PNL	LRM-4D	Norminal	11.19		0.135		0.256		0.229	0.257							
PNL	LRM-5412C	Norminal	10.97				0.148		0.107	0.098	0.008						
PNL	LRM-5412D	Norminal	10.98				0.145		0.088	0.114	0.007						
PNL	LRMS-1C	Analyzed	11.23		0.095		0.166		0.186			0.001					
PNL	LRMS-1D	Analyzed	11.23		0.097		0.166		0.187			0.002					
PNL	LRMSM-1C	Analyzed	11.30	0.019	0.000	0.003	0.193		0.230			0.000	0.008	0.184	0.005	0.004	0.006
PNL	LRMSM-1D	Analyzed	11.30	0.019	0.000	0.003	0.193		0.229			0.001	0.008	0.184	0.005	0.004	0.006